ADVANCES IN AGRONOMY

VOLUME V

ADVANCES IN

AGRONOMY

Prepared under the Auspices of the

AMERICAN SOCIETY OF AGRONOMY

VOLUME V

Edited by A. G. NORMAN

University of Michigan, Ann Arbor, Michigan

1953

ACADEMIC PRESS INC., PUBLISHERS

NEW YORK

ACADEMIC PRESS INC.
125 EAST 23RD STREET
NEW YORK 10, N. Y.

Library of Congress Catalog Card Number: (50-5598)

PRINTED IN THE UNITED STATES OF AMERICA

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Preface

The planning of the volumes of this series is a highly educational experience for the editor, who solicits and receives many suggestions from his colleagues on the Advisory Board and other agronomists. It impresses on his mind the breadth and vigorous development of the field of agronomy, and the diverse interests and accomplishments of those who can be called agronomists, or who work in ancillary fields. With this, Volume V, there will have been published more than forty articles, no two of which cover the same ground. Along with many additional subjects yet to be treated, it is our intention to return to some of these forty topics in later volumes in order to present progress reports on the most recent advances.

In this volume the only new departure is the inclusion of a review of somewhat unusual length, recounting authoritatively the history of the establishment of a major crop in the United States. This crop, wheat, occupies, and has always occupied, a vital place in our national economy and in world trade. At times, as now, there is a domestic surplus; at other times there may be a shortage in world markets; at all times the real need for wheat by the world's population probably far exceeds the supply. Much of it is grown in regions where substitution by other crops is not feasible and in the face of natural hazards that may result in crop failure. By many the adequacy of the domestic supply of wheat is too readily taken for granted. The agronomic advances that have been made with this crop have been less generally recognized and publicized than those with some lesser crops. It is, therefore, salutary to look backward as well as forward in this case in order to see the distance that has been traversed, as well as the paths that lie ahead. This has been done by Dr. Salmon and his colleagues for the U. S., and by Dr. McKibbin and Dr. Goulden for Canada. Taken together, these constitute a comprehensive account of wheat and wheat improvement on the North American continent.

Equally complete, but in a wholly different field, is the review on weathering of minerals, which is the primary and most basic natural phenomenon in soil genesis. It might be argued that this is hardly agronomy, a debate which will not be entertained here. Without ques-

tion, the inherent fertility of soils and hence their productivity stems in great measure from the nature of the parent minerals and the type and extent of the weathering processes.

The policy of surveying the agronomic trends in individual countries is continued in this volume by the inclusion of a review of the pattern of agronomy and horticulture in Canada. It is anticipated that one article of each volume will be of this character.

A. G. NORMAN

Ann Arbor, Michigan
September, 1953

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Compiled by R. R. McKibbin, *Central Experimental Farm, Department of Agriculture, Ottawa, Canada*

Soil Management for Conservation and Productivity

By O. R. Neal, *Camp Detrick, Frederick, Maryland*

A Half Century of Wheat Improvement in the United States

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I. Introduction

A little over fifty years ago Sir William Crookes (1899), President of the British Association for the Advancement of Science, created a mild sensation in the United States and startled his own countrymen by warning them of the "deadly peril of not having enough to eat because wheat production could not keep pace with the increase in population." "It is almost certain," he said, "that within a generation the ever-increasing population of the United States will consume all the wheat grown within its borders and will be driven to import, and like ourselves, will scramble for a lion's share of the wheat crop of the world. The details of the impending catastrophe no one can predict, but its general direction is obvious enough." The president of the British Association was not an alarmist and many authorities agreed with him. One in particular, John Hyde, chief statistician for the United States Department of Agriculture, stated (1899) among other things that "for general agricultural purposes the public domain is practically exhausted and that consequently there can be no further considerable additions to the farm area of this country is too well established to be the subject of controversy."

Allowing nearly a generation for error in timing, it is now clear that these warnings were at least premature, for the United States instead of importing wheat has supplied its own normal needs and produced a large surplus for animal feed, alcohol, and food for her allies, and conquered countries during and after the most devastating war known to mankind. Neither Crookes nor Hyde saw, nor could they have been expected to have anticipated, the tremendous effect that research has had on the capacity of the United States to produce wheat. This is common knowledge today but the details are not well known. Some account of them should be of general interest and also of some value should there be, as some believe, a continuing need for all the United States can produce.

II. Acreage, Yield per Acre, and Production in the United States

1. *Production Trends*

In the five years ending in 1898 the United States produced 596,000,000 bushels of wheat as compared with 1,200,000,000 bushels for the five years ending with 1948, an increase of 604,000,000 bushels or slightly more than 100 per cent. The increase is due both to more acres and to more bushels per acre, as may be seen in Fig. 1, which shows the average acreage, production, and yield per acre by census years or by ten-year periods beginning with 1839. These graphs show that in spite of a marked increase in acreage generally brought about by extension into more hazardous and less productive areas, the average yield per acre has not only been maintained but has increased. If the tendency to exaggerate yields per acre in the early days, as noted by Malin (1944), was generally true, the actual increases are greater than those indicated here.

The harvested acreage and total production have increased almost constantly since 1839. This increase is due mostly to the westward extension of wheat into new farming areas from the Atlantic Coast into western Maryland, Pennsylvania, and New York, thence across Ohio, Indiana, and Illinois into eastern Iowa and southern Minnesota and reaching the eastern part of the Great Plains about 1900. Wheat production began in the Far West before the middle of the nineteenth century and rapidly expanded after the discovery of gold in California in 1849. Ball *et al.* (1921) have given an interesting account of this westward march of wheat. Since 1900 (Baker, 1931) much of the expansion has been into drier and more hazardous areas; this expansion was made possible by technological improvements such as development and use of farm power and improved machinery, better methods of culture, better varieties, more effective control of disease, insect, and weed pests, and by a better knowledge of the relation of the wheat plant to its environment. A significant feature of this development has been a great reduction in the number of man-hours required to produce a bushel of wheat.

Minnesota, which at one time was one of the leading wheat states, now grows scarcely one-fourth as much wheat as fifty years ago and Iowa one-eighth as much. Kansas, on the other hand, grows five times as much, Nebraska twice as much, and Montana and Texas a thousand times as much. Oklahoma, which grew practically no wheat before 1895 and less than 1,000,000 acres in any year previous to 1898, produced an annual average crop in excess of 70,000,000 bushels during the past ten years. Most of the increase in Kansas, Nebraska, Texas, and Montana is on land that produced no wheat previous to 1900. Acreages have

also increased considerably in North Dakota and in the Pacific Northwest, especially in Idaho and Washington, generally into drier and less productive areas. The California acreage and production are only about half what they were before 1900.

The curve of Fig. 1 showing yields per acre is of special interest because yields per acre are often used to measure or indicate technological improvements. They are reasonably good indices in countries in which acreage remains fairly constant or where the productivity of the new acreage does not differ materially from the old. They may be misleading, however, in a country such as the United States, where the acreage has greatly increased into areas where the conditions for growth are quite different. If an improvement reduces cost per acre, thereby permitting a larger expansion on less productive land, average over-all acre yields may actually be reduced.

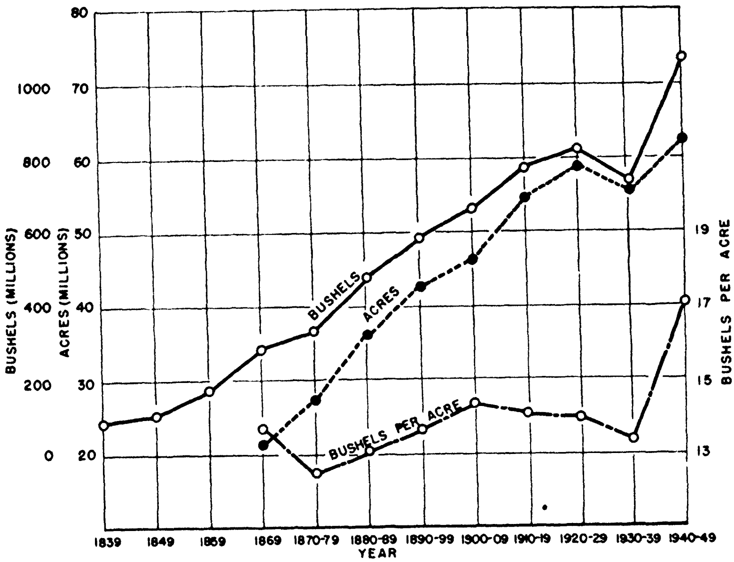

FIG. 1. Production of wheat in the census years 1839, 1849, 1859, and 1869 and average acreage, production, and yield per acre by ten-year periods in the United States from 1870 to 1949.

The primary objective of the United States farmer has been to grow more bushels at a minimum of cost and inconvenience. He takes considerable pride in growing a good crop, but he is vitally concerned with large yields per acre only to the extent that it contributes to his net income. The profit from wheat relative to that of other crops also has a marked influence. If a new variety or a better cultural method results

in larger yields per acre, it may mean that wheat can be grown at a profit on less productive land. Given reasonably high prices or prospects of such prices, the natural tendency is to increase production. A decrease in crop acreage such as has taken place in the eastern United States may mean a larger proportion of wheat on better land and hence larger over-all yields per acre, even though there may have been no improvement in technology.

The fact that yields per acre are based on harvested and not seeded acres should also be considered. In some years much wheat was seeded that was not harvested, as shown in Fig. 2. The abandonment was espe-

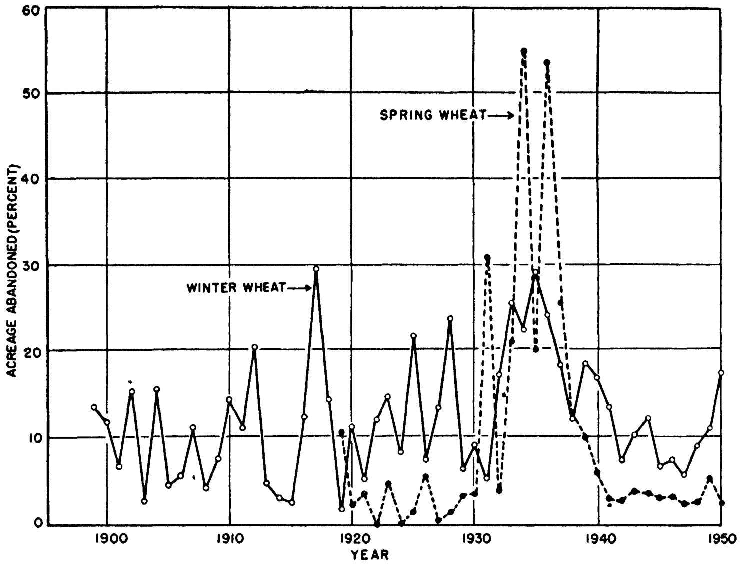

FIG. 2. Acreage of winter and of spring wheat seeded in the United States but not harvested.

cially heavy during the drought years 1933–1937, when the average exceeded 20,000,000 acres or 28 per cent of the seeded acreage. Abandonment of winter wheat was heavy in 1912 and 1928, largely because of winterkilling in Ohio, Indiana, and Illinois; in 1917, because of winterkilling in Nebraska and Kansas; and in 1925, because of winterkilling in Washington, Oregon, Montana, and Texas.

Finally, it should be noted that the environmental conditions under which wheat is grown today are different from those of fifty years ago, even in the same areas. In some cases soil fertility has declined and in many cases there has been an increase in insect, weed, and disease pests, in accordance with the well-known principle that concentration and con-

tinuation of a particular crop favors the pests peculiar to that crop. Research unquestionably has aided in keeping these under control; without research, acreages and yields per acre would probably be less than they were in 1898.

The decline in yields per acre from 1900–1909 to 1930–1939 shown in Fig. 1 is due largely to expansion into drier areas of the western Plains and to the unprecedented drought during the mid-thirties. The marked per acre increase for the 1940–1949 period, on the other hand, was due in part to more favorable weather, to better varieties, to more extensive use of fertilizers and pesticides in some sections, and to more timely operations made possible by mechanization. Favorable prices during this period, which permitted and encouraged the use of technological improvements, and better informed farmers as compared with earlier periods are some of the other factors that should be recognized. It is not possible on the basis of available information to evaluate these various factors separately, but some evidence of the importance of particular ones will be presented later.

Figures 3, 4, 5, and 6 give similar information for the principal wheat states in the southern Great Plains, in the northern Great Plains, in the Eastern States, and in the Pacific Northwest, respectively. Each of these areas is relatively homogeneous as compared with the United States as a whole.

a. The Southern Great Plains. Yields per acre in the southern Plains have been relatively constant in spite of an enormous expansion in acreage into western Kansas, Nebraska, Oklahoma, and the Panhandle of Texas. These are areas which up to about World War I were generally considered too dry to produce wheat economically. A period of unusually high precipitation from about 1905 to 1915, aided and abetted by real estate promoters and other enthusiasts, stimulated an extensive influx of settlers and homesteaders into these drier areas. Many of them failed because the information on which a sound agriculture could be based was completely lacking, as we now know.

b. The Northern Great Plains. Excepting the ten-year period ending in 1949, yields per acre have declined almost constantly in the northern Great Plains, owing (1) to expansion into drier areas west of the Missouri River and (2) to increasing damage from stem and leaf rust, from scab, and from weeds in the eastern half of the area. The severe drought of the mid-thirties plus a severe stem rust epidemic in 1935 and extensive damage from leaf and stem rust in 1937, 1938, and 1941 are primarily responsible for low yields during those years. Both the northern and southern Plains have been favored by above-average rainfall during the past ten years. However, Heisig *et al.* (1945) have shown that yield

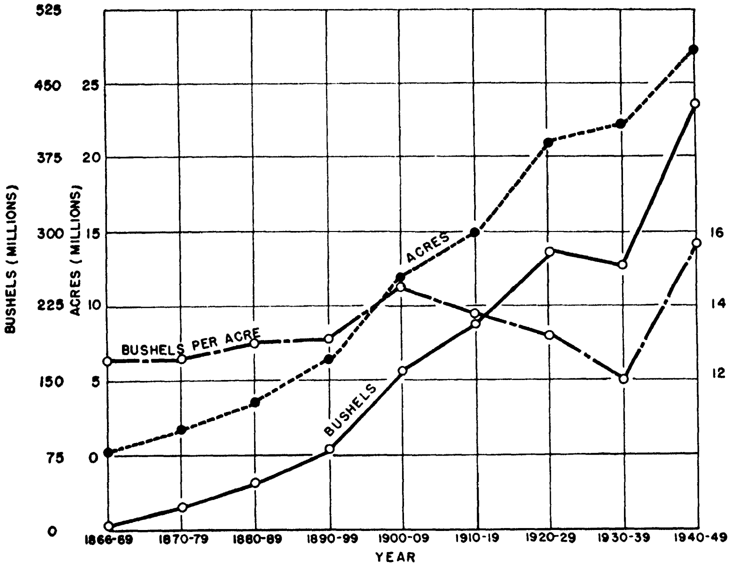

FIG. 3. Average acreage, production, and yield per acre of wheat in Kansas, Nebraska, Colorado, Oklahoma, and Texas for 1866 to 1869 and by ten-year periods from 1870 to 1949.

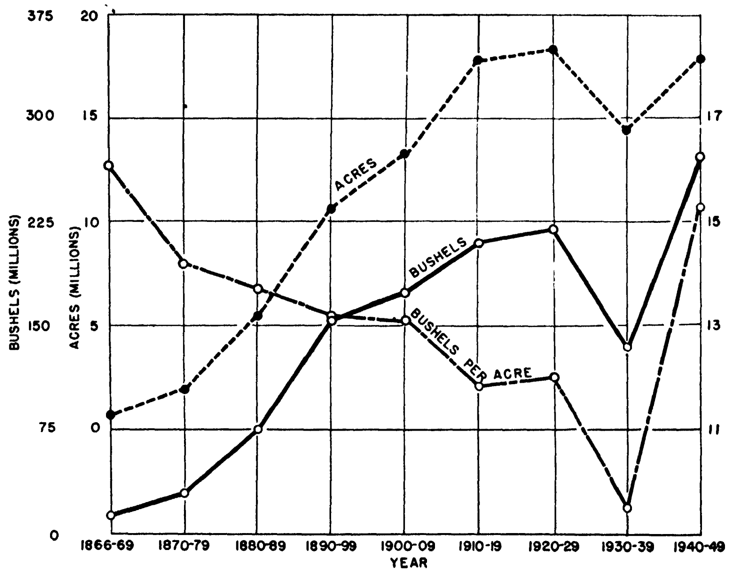

FIG. 4. Average acreage, production, and yield per acre of wheat in Minnesota, North Dakota, South Dakota, and Montana for 1866 to 1869 and by ten-year periods from 1870 to 1949.

per acre trends in North Dakota and in Kansas for the period 1920–1945 are definitely upward even after they are adjusted for precipitation and temperature effects. The indicated increase for Kansas during this period is slightly more than 2 bushels per acre and that for North Dakota, about 4 bushels per acre. An important factor in the northern Plains is the relative freedom from damage by stem rust since 1940.

c. The Eastern States. In the eastern United States the acreage of wheat has constantly declined to but little more than half that of the peak period, 1880–1889. Yields per acre have constantly increased.

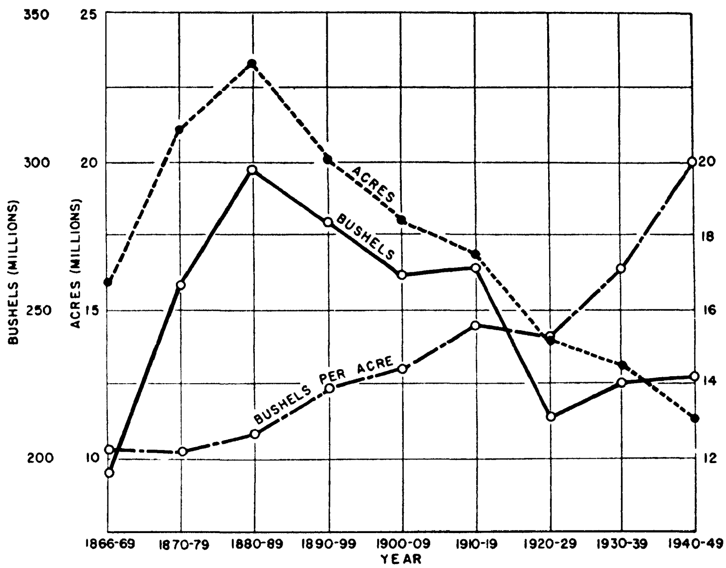

FIG. 5. Average acreage, production, and yield per acre of wheat in the Eastern States for 1866 to 1869 and by ten-year periods from 1870 to 1949.

partly as a result of growing wheat on the more productive land while reverting the poorer land to pasture and timber. Baker (1937) showed a marked decline in the acreage of all harvested crops in the eastern United States, especially from 1919 to 1928. Johnson (1929) also mentions elimination of much of the poorer wheat land as one of the reasons for the increase in yields of wheat in Pennsylvania. Lamb (1932, p. 15) has shown that in Ohio wheat now occupies a smaller per cent of the improved land than formerly. Wheat in the Eastern States is grown almost exclusively in rotations with other crops. As Lamb (1932) pointed out, the adoption of a rotation system of farming, and then of longer rotations involving more spring grains, resulted in a decrease in the wheat acreage. The constant and very material increases in yields

per acre in the eastern United States has been due principally to more fertilizers, better varieties, and more timely operations made possible by power machinery.

d. The Pacific Northwest. Figure 6 shows the acreage, production, and yields per acre in Washington, Oregon, and Idaho. Acreage increased constantly until 1920–1929 and then leveled off at slightly less than 5,000,000 acres. Yields per acre are relatively high, partly because most wheat in this area is grown on summer fallow. Yields per acre gradually increased up to 1930–1939, and much more rapidly thereafter, owing in part to more favorable weather and also to a considerable de-

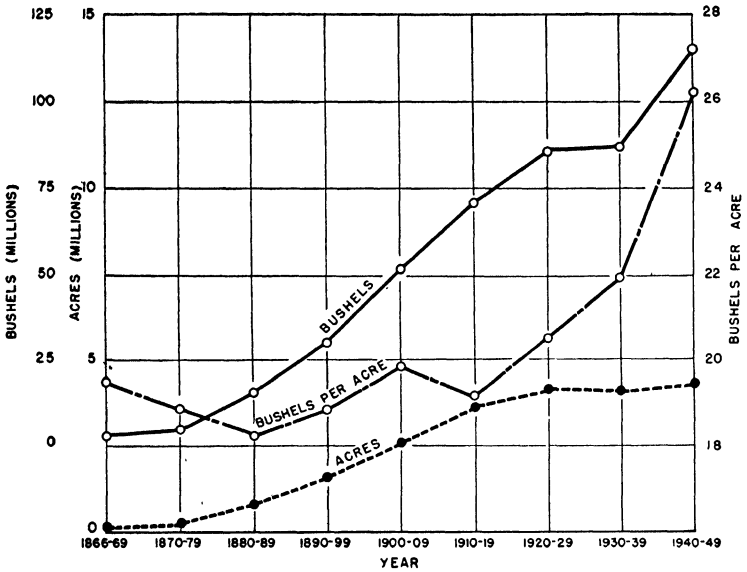

FIG. 6. Average acreage, production, and yield per acre of wheat in Washington, Oregon, and Idaho for 1866 to 1869 and by ten-year periods from 1870 to 1949.

gree to better varieties produced during this and earlier periods, and to better cultural methods.

e. Development of the Durum Wheat Industry. The durum wheat industry of the United States has been developed almost entirely since 1900. According to Carleton (1900, p. 19) a few thousand acres were grown before that time in Texas and still are, although the amount is insignificant in relation to the total. Also a small acreage was grown in North Dakota from seed brought in by Russian emigrants at least as early as 1893 (Shepperd and Ten Eyck, 1902). At the present time more than 85 per cent of the durum wheat is grown in North Dakota, principally in the eastern part of the state, west of the Red River Valley,

but extending into western Minnesota and northeastern South Dakota. The principal advantage of the durum wheats is resistance to the races of leaf and stem rust that prevailed previous to 1950 and an ability to outyield common wheats in the durum area.

According to Ball and Clark (1918) durum wheat was first introduced into the United States in 1855 but never took hold, largely because it lacked a market and partly perhaps because it was tried only in the Eastern States, where it is not adapted. The early development of the industry was due largely to the initiative and vision of M. A. Carleton, cerealist of the United States Department of Agriculture, who made a

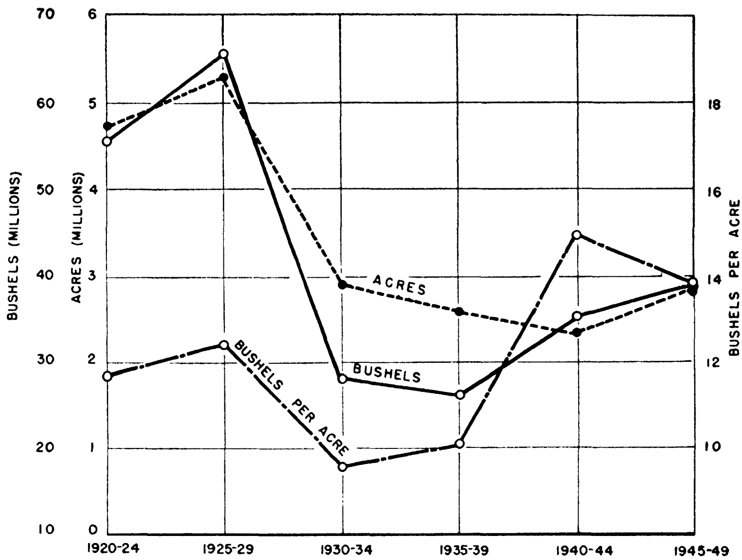

FIG. 7. Average acreage, production, and yield per acre of durum wheat in the United States by five-year periods from 1920 to 1949.

trip to Russia in 1898–1899 and again in 1900 and made a thorough study of the durum wheat production in that country. He was greatly impressed with the similarity of the climate and soil of this area to that of the Great Plains of the United States and recommended the growing of durums in the latter area. He was particularly impressed with what he believed to be their drought resistance, and accordingly recommended them for the drier portions of the Great Plains. He states (1901, p. 11): "They stand foremost among all wheat crops in their excellent adaptation to heat and drought." In a map of the United States published in 1900, he pictured the durum wheat area as comprising north central Texas, western Oklahoma, and extreme southwestern Kansas. In

a later map (1901, p. 20) the recommended area extends in a wide belt comprising most of the Great Plains from Mexico to the Canadian border.

As we now know, durums are not so resistant to heat and drought as many adapted common wheats. They produced slightly higher average yields than the common spring wheats in the drier areas, but the difference was not enough to offset the difference in market price. Carleton recognized their leaf-rust resistance but considered this relatively unimportant. He did not realize that they were also resistant to stem rust until after the severe and widespread epidemic of stem rust in 1904.

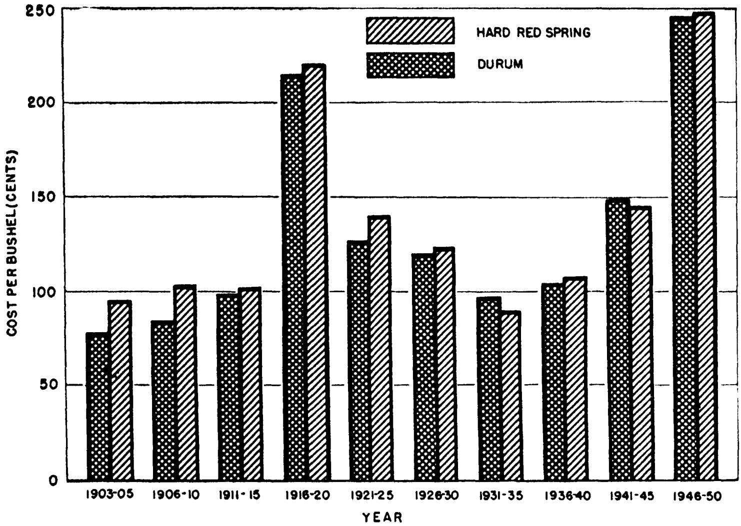

FIG. 8. Average prices of hard red spring and durum wheats at Minneapolis, Minnesota, for 1903 to 1905 and by five-year periods from 1906 to 1950. (Prices for hard red spring wheat are for No. 1 Northern Spring, and for durum, No. 2 Amber Durum from 1903 to 1933 and No. 2 Hard Amber Durum from 1934 to 1950.)

Official estimates of the acreage and production of durum wheat as distinct from hard red spring wheat were first made for North Dakota, South Dakota, and Minnesota in 1909 and for the United States as a whole in 1919. Carleton (1901) estimated that probably 75,000 to 100,000 bushels were produced in 1901, and Ball and Clark (1918) state that about 50,000,000 bushels were produced in 1906. The acreage, production, and yield per acre from 1919 to 1950 are shown in Fig. 7.

Acreage and production, it will be noted, reached a peak in the period 1925–1929 and then declined sharply to about half of the maximum, principally because of a marked price differential in favor of the common spring wheats. Another important fact, as pointed out by Waldron

(1947), was the development of early-maturing, rust-resistant, high-yielding common spring wheats beginning with CERES, eliminating most of the advantages enjoyed by durum wheats. The prices were much less for durum than for common spring wheat until about 1911, then nearly equal up to and during World War I, followed with a decline soon after the war, as shown in Fig. 8. Since 1930 the price of durum has been about equal to, or above, that of hard red spring wheat.

The relatively low yields per acre during the 1930–1934 and 1935–1939 periods were due largely to unfavorable weather. The higher yields for the 1940–1944 and 1945–1949 periods were due to more than usually favorable weather and to the absence of severe damage from stem rust.

2. The Preresearch Era

Mr. William White has suggested that if one wants to study capitalism one of the best ways is to go where there isn't any. Much can be learned about research in the same way. Since wheat production before the present century in what are now the principal producing areas was largely without benefit of research, a study of this period should be informative. Malin (1944) has provided useful background information for such a study in his agricultural history of four counties (Riley, Geary, Dickinson, and Saline) in east central Kansas, and much additional information is available in the reports of state boards of agriculture and agricultural experiment stations of the various states, in the reports of the United States Department of Agriculture, and in the farm press. Kansas is an especially fertile field for study because it is now the leading state in wheat production, because it was one of the first of the states of the Great Plains to be settled, and because the problems of the early Kansas wheat grower were at least as numerous, as important, and as difficult of solution as those of any other state.

a. Early Developments in Kansas. According to Malin, wheat was grown in eastern Kansas as early as 1839, when 100 acres near Topeka were harvested. It was seeded near Junction City, about 140 miles west of Kansas City, in the fall of 1855, and increased rapidly thereafter in the surrounding territory. Settlers coming to Kansas brought seed supplies, implements, and the methods and philosophies that prevailed in the country from which they emigrated. Most of these were poorly adapted to the new environment. Some adjustments or changes were made quickly, but others came about very slowly.

Slow but powerful oxen broke much of the prairie for the earliest settlers, but horses and mules were soon substituted for them. The tractor was not used for land preparation until well along in the present century. Broadcasting the seed was a common practice; as we now

know, this must have resulted in many heart-breaking disappointments because of poor stands and winterkilling. It was not until about 1869 or after some fifteen or twenty years of experience that farmers were sufficiently convinced of the advantage of drilling to ship in a substantial number of drills. Considerable wheat seems to have been broadcast even as late as 1880. Soft winter wheat and spring wheat, the latter at first predominating, were the only kinds grown. Both are much more susceptible to injury by rust, and the soft winter wheat is more easily winterkilled than are the hard red winter varieties generally grown now or even than were those that were common at the close of the century. Losses from rust and winterkilling were severe (Malin, 1944). Experimental evidence secured in recent years indicates that the soft winter varieties then grown yielded no more than two-thirds as much, and the spring wheat no more than one-third or one-half as much, as the TURKEY wheat grown somewhat later. But nearly twenty-five years' experience was required to induce farmers to abandon spring wheat and nearly thirty years elapsed after the introduction of TURKEY wheat before farmers generally were convinced that it was better than the soft winter wheats. Contrast this with recent Kansas experience in which three varieties, PAWNEE, COMANCHE, and WICHITA, almost unknown to Kansas farmers in 1944, occupied 71 per cent of the acreage in wheat in 1952; or with the spread of THATCHER in the northern Great Plains from a nominal 20,000 acres in 1935 to nearly 12,000,000 acres in the United States and 5,500,000 acres in Canada by 1941.

Little was known about the best preparation of the land or time of seeding in the Great Plains or about the control of rust, smut, grasshoppers, chinch bugs, and Hessian fly. Time of seeding was a debatable question as late as 1920. It still is, though to a very minor extent as compared with fifty to seventy-five years ago. Much wheat was sown too early and winterkilled. This caused reaction to the other extreme, which also resulted in winterkilling or a late harvest and in more than average injury from rust, drought, or high temperature. Much of the wheat dried out before winter because it had been seeded on land that had not been prepared until near seeding time, and the remainder often produced low yields because the growth of weeds between harvest and seeding had used up the available moisture and nitrates in the soil. Substantial improvements in tillage were made from time to time, but there was no concerted effort to prepare the ground immediately after harvest until about the second decade of the present century. Experiments by the Kansas, Nebraska, and Oklahoma Experiment Stations showed very material advantages from early soil preparation, and the advent of the tractor made this possible.

Losses from winterkilling were frequent and severe before the present century. Malin states that abandonment of winter wheat acreage ranged up "to 75 or 80 percent and probably oftener than not was 25 and 50 percent." This, no doubt, was due to failure to get stands, to drought, grasshoppers, and Hessian fly as well as to freezing during the winter or early spring. He mentions winterkilling specifically as having been recorded in nineteen of the forty-five years between 1855 and 1900. It certainly has not occurred in anything like the same proportion of years since 1900 to a sufficient degree to attract notice in the farm press or official reports. McColloch (1923) has noted eight outbreaks of Hessian fly in Kansas up to 1916, six of which occurred previous to 1900 and each of which was generally more widespread and severe than the one that preceded it.

Malin mentions damage from rust in five of the forty-five years, stem rust in two years, and kinds not specified in others. Remembering that late-maturing, rust-susceptible varieties of spring wheat comprised an important part of the acreage up to about 1880 and that rust-susceptible varieties of soft winter wheat made up most of the remainder until about 1900, it seems probable that rust caused more frequent damage than is here suggested. Carleton (1896, p. 498) mentions the "blasting effects" of rust, principally stem rust, in the "Southern latitudes," and states that wheat growing in vast areas of Texas had been abandoned on account of rust. Although Carleton mentions Texas specifically, he certainly had Kansas in mind, considering that one of the principal objectives of a breeding program inaugurated there in 1899 was to produce rust-resistant varieties.

The shift to hard winter wheat also resulted in an improvement in quality, including plumper grain higher in test weight and yielding more flour per bushel. Malin cites data compiled by McFarland of the United States Department of Agriculture for the years 1876–1883 in which test weights ranged from 53.1 to 57.3 and averaged 54.6 pounds per bushel. The areas represented by these data are not known, but it appears that test weights of wheat have been much improved. The average test weight of hard red winter wheat inspected at Kansas City for the years 1923–1932 was 59.1, and the least for any year (1923) was 57.1.*

b. Early Wheat Growing in Nebraska. In Nebraska spring wheat predominated until after 1900, and winterkilling of the soft winter wheat was even more severe than in Kansas.

* "Grain Inspectors Letter" June 17, 1933. Grain Division, Bur. Agr. Econ., U.S. Department of Agriculture.

Some measure of the benefit derived from the general culture of TURKEY wheat in Nebraska after 1900 is afforded by comparing its average yield with that of spring wheat at the North Platte Station in western Nebraska. During the twenty-eight-year period ending in 1939, as reported by Quisenberry *et al.* (1940), winter wheat yielded on the average 20.6 bushels as compared with 14.3 for spring wheat, a gain of more than 44 per cent. At Lincoln, in eastern Nebraska, the corresponding gain for a thirty-one-year period is 14.2 bushels or 96 per cent.

c. Early Wheat Growing in the Northern Great Plains. Wheat production got off to a better start in the northern Great Plains than in the states to the south. The new settlers were fortunate in having FIFE and BLUESTEM, varieties that were reasonably well adapted. Winter wheat was winterkilled so completely in most areas there was no temptation to grow it, and late-seeded spring wheat was so obviously inferior that early seeding soon became the prevailing practice. Broadcasting was more successful than in the winter wheat belt because soil moisture usually was adequate at seeding time. Diseases (excepting bunt) and insects appear to have been less destructive than in the southern Plains and also less than since 1900. Weeds were not an important factor on the new lands until near the end of the century. Settlement of much of the drier, consequently more hazardous, areas west of the Missouri River did not occur until after the close of the century.

Stem and leaf rust, foot rots, scab, and most other diseases appear to have been relatively unimportant in comparison with later periods, and stem and leaf rust less important than in the southern Great Plains in the same period. Apparently the only severe widespread rust epidemic in this area previous to 1900 was in 1878, as reported by Hamilton (1939). Bunt was important, since Carleton (1896, p. 496) states that the "millers complain of it constantly," and Gussow and Conners (1927) state with reference to a contiguous area in Canada that "previous to 1900 bunt was alarmingly serious and threatened to be a limiting factor in wheat production." Wheat scab apparently was not serious in Minnesota and the eastern Dakotas until after corn became an important crop, mostly after 1900. Methods for treating seed for the control of bunt were known and, though less effective and convenient than those now available, were used when the losses became too great.

Probably there was some improvement in varieties resulting from the selection of pure strains such as POWER from RED FIFE, and HAYNES BLUESTEM OR MINN. NO. 169 from BLUESTEM between 1885 and 1900 (Clark and Bayles, 1942; Stoa, 1921; Hays and Boss, 1899; Atkinson and Donaldson, 1916; and Champlin, 1914). PRESTON, introduced from Canada in about 1895, was not grown extensively before the close of the century.

The improved varieties could not have had any great effect until after 1900 because distribution of the seed was not general until late in the century.

d. Developments in the Pacific Northwest. The first wheat known to have been grown in the Pacific Northwest was raised on Vancouver Island in 1825 (Swenson, 1942). The discovery by Hendry (1931) of remnants of club varieties, similar to those grown in modern times, in adobe houses constructed between 1700 and 1800 indicates an earlier date for California. Production both in California and in the Pacific Northwest increased after the California gold rush of 1849, and again in the Pacific Northwest after the discovery of gold in British Columbia and Montana in the 1850's, but did not really get under way on an extensive scale until sometime after eastern Washington, eastern Oregon, and northern Idaho, known as the Inland Empire, was opened up to settlers by the building of the railroads in the 1880's. Production in Utah and southern Idaho, though never great in relation to national supplies, began in the early 1880's but was not of much significance other than locally until after the close of the century.

Early settlers in the Inland Empire attempted to crop the land each year, but the yields were so low that alternate cropping and summer fallow soon became the general practice (Hunter *et al.*, 1925). Horses and mules were used for power; the grain was cut with a header and either stacked or hauled directly to the thresher. Except in the Walla Walla area the combine was not introduced into this section until after the end of the century. Wheat raising in the Inland Empire began with two- and three-horse teams, but these were soon replaced with larger and larger outfits. Standard equipment consisted of eight-horse or ten-horse teams pulling three-bottom plows, with occasionally twelve- to twenty-horse teams hitched to larger or multiple units (Hunter, 1927) (Fig. 9).

Production depended mostly on soft white spring varieties, usually seeded in the fall, often "with disastrous results when a cold winter occurred" (Gaines, 1941). These were mostly LITTLE CLUB in the Palouse (eastern Washington), PACIFIC BLUESTEM in the Big Bend country, and RED CHAFF in the area between. The late-maturing variety JENKIN was grown to some extent near Walla Walla, Washington, and Pendleton, Oregon.

The winter varieties RED RUSSIAN, GOLDCOIN (FORTYFOLD), and JONES FIFE made their appearance in the late nineties. They later became locally important but too late to make any significant contribution before the end of the century. All were very susceptible to stinking smut or bunt, a point of great importance later, and GOLDCOIN and JONES FIFE

shattered badly. Stephens and Hyslop (1922) have estimated the annual loss from shattering of GOLDCOIN in Oregon at 2 to 3 bushels per acre.

In 1899, W. J. Spillman of the Washington Station made the first of his famous crosses, which later contributed so much to the welfare of the Pacific Northwest. His stated objective was to produce winter-hardy, stiff-strawed, nonshattering prolific varieties. None of the progeny was available for distribution until after the turn of the century.

So long as farmers grew spring wheat and seeded it in the spring, bunt or stinking smut was kept under control by seed treatment. This was no longer effective with the change to fall seeding of spring wheat

FIG. 9. A combined harvester–thresher drawn by thirty-two horses in a wheat field near Moro, Oregon, in 1914.

and later to winter wheat near to and after the close of the century because of the survival of smut spores in the soil. This illustrates one of the most underrated phenomena in agriculture: the introduction of new and unsuspected problems with changes in agricultural practices.

e. Wheat in California. The possibilities of growing wheat on a large scale in California seem to have been first realized about 1860. Large tracts of land in the interior valleys secured at a nominal price afforded the basis for a rapid expansion beginning in about 1870 and continuing for some twenty or thirty years. Individual farms often comprised 20,000 to 30,000 acres. In choosing methods of culture the aim was to keep costs at a minimum rather than to obtain large yields per acre. The ground was plowed shallow, and seed was sown broadcast and cov-

ered by harrowing. Often a broadcast seeder was attached behind the plow and a harrow behind that so that plowing, seeding, and harrowing were all accomplished at one operation. The poorest grain of the previous year often was used for seed (Blanchard, 1910). Weeds increased because of careless methods, and "grew rampant throughout the region" before the end of the century. Because of the weeds and low rainfall, summer fallow every third year and finally every other year soon became the dominant cropping system. Even the summer-fallowed land was often "exceedingly foul" because of careless or improper methods. The header and stationary thresher were used at first for harvesting and threshing the crop; the large combines drawn by a twenty-eight- to forty-horse team or by a steam engine (Fig. 10), for which California

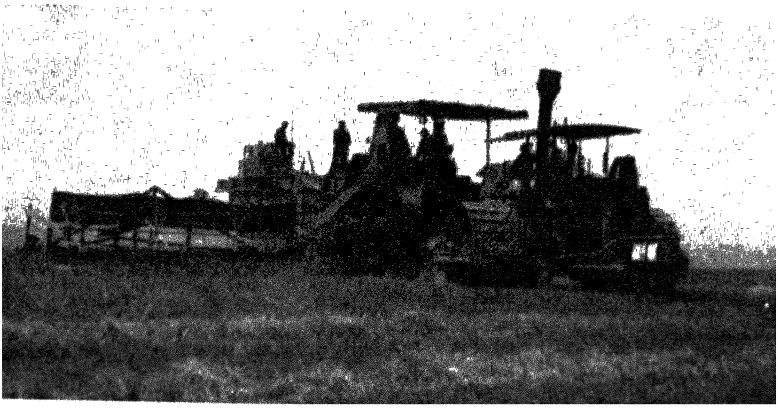

FIG. 10. A steam-powered, combined harvester–thresher such as were use in California in about 1890.

became noted, were adopted about 1880. Before the end of the century, California led the world in the use of labor-saving machinery. Though no figures appear to be available, it is doubtful if more wheat had been raised per man-hour of labor anywhere in the world up to that time.

Wheat production in California has from the first depended on spring varieties, seeded, however, in the fall or early winter. They are not only sufficiently resistant to cold to survive the mild winters, but their upright, vigorous growth was soon found to be advantageous in competing with weeds. LITTLE CLUB, PACIFIC BLUESTEM (or WHITE AUSTRALIAN), SONORA, and PROPO were the principal varieties.

Previous to 1900 any improvements in per acre yield resulting from a choice of better varieties and from the increasing use of fallow probably were more than offset by the increase in weeds.

f. Wheat Growing in the Eastern States. Wheat production in the eastern United States began along the Atlantic coast about 1618, pushed westward with the settlers, and crossed the Mississippi River by 1840. It was then grown in every state east of the Mississippi that now produces any significant amount. From then on the acreage increased steadily and rapidly until about 1880, then leveled off to the end of the century, after which there has been a considerable decline. Yields per acre appear to have increased between 1 or 2 bushels per acre from 1866, the first year for which data are available, to 1900.

Production began with primitive methods and crude implements. Land was plowed or stirred with a wooden plow with steel strips on the mold board, seeded largely by hand, cut with a sickle or cradle, and threshed with a flail or by tramping by animals. The cradle was not introduced until about 1800. The steel plow came into use about 1833, the simple reaper about 1830, the self-rake reaper about 1850, the wire binder about 1865, the twine binder about 1880, and mechanical threshers about 1850.

The first varieties came from northern and western Europe with the early settlers. Of the few known varieties that were grown during the eighteenth century, RED MAY, GOLDCOIN, PURPLESTRAW, and MEDITERRANEAN survive today, though they are probably not precisely the same as when introduced. During the later part of the nineteenth century there was much interest in bringing in new varieties from abroad; this indicates that there was an interest in improvement, and later in making selections and in crossing. Ball (1930) has reviewed these contributions, and there is no need to repeat them here.

In the Eastern States research undoubtedly played a more important role in wheat production before 1900 than it did in the western United States. The agricultural colleges and experiment stations of Connecticut, Pennsylvania, Ohio, Illinois, and Michigan not only brought the research findings of the Old World to the new country but contributed many of their own.

There were many private experimenters and much of the information, especially as regards fertilizers and land management, derived from Bouissingault's experiments in France, from Liebig's laboratory in Germany, and from the Rothamsted Station in England was brought to the United States and adapted to the somewhat different environment. It is significant that this could be done with far greater success than could the results of experiments in the eastern United States, of a later date, be translated into useful deductions for the Great Plains. This is because the eastern United States is much more like England and France than

it is like the Great Plains. Nevertheless, it is reasonably clear that progress during this period was relatively slow.

On the whole, it seems safe to conclude that there was considerable improvement in methods of wheat production in the United States previous to 1900. Perhaps the outstanding features of the period are the slowness with which improvements were made in most cases, the relative simplicity of those that were made without benefit of research, and those, such as the introduction of TURKEY wheat, that were made without conscious effort to do so.

3. *The Propaganda Era*

Superstition and wishful thinking had a place in the thinking and literature of the eighteenth and nineteenth centuries, the importance of which it is now difficult to appreciate. Potatoes often were planted according to the phases of the moon. A farmer was much more likely to consult his almanac than the experiment station (when there was one) to determine when to sow wheat, corn, or other crops. Many believed in changing seed instead of improving what they had. The rain maker had his following in every unusually dry year. Real estate agents and promoters in general fostered the belief that the climate was changing for the better and that rainfall would increase with the plow, the building of dams to hold water, and the planting of trees. Shelter-belt and rain-making enthusiasts of our own day could, no doubt, add to their repertoire of ideas by searching the files of old newspapers of the period. Not the least of the benefits we now enjoy as a result of research is the partial release from the superstitions, propaganda, and wishful thinking of this period.

Chandler (1942) has referred to the first ten or fifteen years of the present century as the propaganda era in agricultural education. These were the days of the dust mulch, deep plowing and dynamiting, corn shows, ear-to-row methods of breeding corn, improvements of small grains by mass selection and by continuous selection, harrowing winter wheat in the spring to conserve moisture, ALASKA and MIRACLE wheat and other phenomenal varieties that would produce maximum crops with one-fourth or less the usual quantity of seed, etc. One of the most publicized of these was the combined recommendation of deep plowing, subsoiling, or dynamiting, and use of the soil or dust mulch. According to a popular version the soil must be loosened to a considerable depth to permit penetration of plant roots and of water, and it must be cultivated after every rain to prevent capillary movement of the moisture to the soil surface, where it would be lost by evaporation. The soil was compared to a cistern, the capacity of which depended on depth of plow-

ing and in which loss of water must be prevented by a cover, the dust mulch. One writer, more dramatic than accurate, admonished the farmers as follows: "Cultivation!, Cultivation!, and more cultivation must be the cry of the dry farmer who battles against the water thieves of an arid climate."

It was not known, or the facts were conveniently ignored, that both roots and moisture penetrate unstirred subsoil; that water sometimes enters unplowed land faster than it does plowed land; that capillarity pulls water downward with as much force as it does upward where there is no water table, as in most of the Great Plains; that plowing 8 or 12 inches deep may be expected to cost four and nine times as much, respectively, as plowing 4 inches deep; that deep plowing and subsoiling in experimental plots had failed to produce any material increases in yield; and, finally, that finely pulverized soil blows.

The soil mulch theory, which was promoted mostly in the Great Plains and the intermountain area, had its counterpart farther east in the corn shows. Originally inaugurated for the laudable purpose of increasing interest in corn improvement by selection, they probably did as much harm as good by promoting the belief that selecting uniform ears with deep kernels would increase the yields, whereas experiments later showed that shallower, smooth types were more productive.

The agricultural experiment stations, which had scarcely got on their feet, were caught in an embarrassing position. Several had reported experimental results that did not support the current propaganda. But these experiments were not numerous and had been conducted for only three or four years, and the presumably anomalous results could be explained by differences in soil type or by other unusual circumstances. Most of the main stations were located in areas of fairly high rainfall not typical of the dry-land areas, and branch stations, especially in the more hazardous areas, were just being established. If the stations took a less vigorous stand against some of the propaganda of the times than, as it now seems, would have been desirable, it should be recalled that they had but little experimental evidence to support any opinions they might express. Besides, all was not propaganda; there was an element of truth in much that was said and written, and it was much easier and more popular to accept plausible cures for obvious problems than to convince legislatures of the need of spending good money for sound research. It was not until results from the well-planned and well-executed experiments in dry-land agriculture conducted by the United States Department of Agriculture in cooperation with the various state agricultural experiment stations became available that excessively deep plowing, subsoiling, dynamiting, and the dust mulch were no longer recommended.

Current propaganda has gone to the other extreme—it is now folly to plow at all—but it has little effect as compared with that of the earlier period, because there is so much experimental evidence to refute it. We may have dust storms again, perhaps rivaling those of the early decades of the century or those of the dry 1930's, but if so it will be mostly because measures known to be effective will not have been used.

4. *The Modern Research Era*

Although agricultural research had considerable effect on wheat production in the eastern United States during the nineteenth century, it had very little effect on that of the Great Plains and of the Far West until after the close of the century. The state agricultural experiment stations got under way immediately after the passing of the Hatch Act in 1887, but time was needed to acquire land, construct buildings, assemble staffs, make plans, and accumulate data. It was then known almost as well as it is now that dependable recommendations relating to growing crops could not be made on the basis of only one or two years results, and that results secured at one place could not be safely applied to all areas even of the same states. This called for the establishment of branch stations, of which there are about 200 at the present time, and in addition many states have outlying fields which differ from branch stations mainly in that their scope and activity are much more restricted and in that they are often temporary. Neither branch stations nor outlying fields were numerous until after the first decade of the present century.

It was during the first and second decades of the century that Mendel's laws began to be applied generally to the improvement of wheat and other crops. The rediscovery of these laws had placed a powerful tool in the hands of plant breeders, but they needed time to learn how to use it and to forge supplementary tools. Plant pathologists still depended on natural epidemics to study plant diseases instead of producing artificial ones when and where they were wanted and under controlled conditions. The existence of physiologic races of bunt, rust, and other disease organisms had yet to be demonstrated. Instead of selecting corn by the score card or by the ear-to-row method we now have hybrid corn, credited with adding 700,000,000 bushels or more each year to the production of this important cereal. Instead of mass selection of small grains we have new varieties that combine the merits of several, produced by the experiment stations and distributed to growers through various state crop improvement associations.

Although it is therefore an oversimplification of facts to designate the period 1910–1915 as the beginning of the modern research era, it can

be justified on the basis of convenience since it was during this period that research assumed a more and more important role in agricultural production.

In attempts to improve crops either by cultural methods or by breeding, yield per acre was the measure of success most generally recognized at the beginning of this era. Quality of the product was occasionally considered. These are still important objectives, but more and more it is being recognized that yield and quality are end results and can be achieved more certainly and efficiently by considering the individual genetic and ecological factors that govern them. Also it is recognized that other characteristics such as tendency to shatter, to lodge, to winter-kill, and to germinate in the shock, and susceptibility to disease are often as important as is yield. Recognition of these relations has led to more basic studies of diseases and insects, methods of controlling them, and means of producing artificial epidemics so that they may be studied more effectively and resistant varieties and selections more easily identified. It suggests the need of more basic knowledge of the ecological factors governing adaptation, a study, however, for the most part left to the future.

An important feature of research with wheat during the last fifty years is the development of cooperative coordinated research programs between state experiment stations in more or less homogeneous regions and the United States Department of Agriculture. Probably the first of these, which, however, was limited in scope and very informal, were the comparisons at stations in the Great Plains of durum and other varieties of wheat introduced from Russia and other foreign countries. The first extensive coordinated program was initiated by the Office of Dry Land Agriculture, United States Department of Agriculture, in cooperation with various states in 1906 to study cultural methods and crop rotations in the Great Plains. A coordinated cooperative breeding program for spring wheat in the northern Great Plains was inaugurated in 1928, a similar one for wheat in the western United States in 1930, and one for hard red winter wheat in 1930. A uniform winter-hardiness nursery for the Eastern States was set up in 1932 and later expanded to include yield, quality, resistance to diseases, and other characteristics of varieties of wheat of interest or importance to the region. A later development was the establishment of the wheat-quality laboratories, of which there is one for each of the four principal wheat regions, the primary functions of which are to investigate wheat-quality problems and evaluate the quality of new varieties produced by breeders. Results from all stations participating in a planned cooperative experiment are made available to each cooperator in mimeographed annual reports. Certain experiments,

but not all, are conducted uniformly at all stations or groups of stations in each region each year.

III. Improvement in Cultural Practices

The culture of wheat has been improved as a result of (1) advances in cultural practices, (2) improvement in equipment, and (3) increase in fundamental knowledge that helps determine the best practices for a given set of conditions. These improvements are interrelated, and their effect on production is a combined one. Knowledge of an improved practice is of little use to one unable to carry it out. Better and improved equipment permit many practices that would not have been feasible fifty years ago.

1. *Early Cultural Practices*

Wheat growing in the Eastern States was fairly stable even at the beginning of the century. European experience adapted to the area by cut-and-try methods plus experimental results at several state experiment stations were reasonably good guides to practice. On the semiarid lands of the Far West, a winter-rainfall region, wheat was grown largely by a system of alternate fallow and wheat beginning about 1870.

The situation was quite otherwise in the Great Plains. The drier portions had experienced several waves of partial settlement followed by depopulation, the latter usually due to a combination of drought and grasshoppers, plus unadapted cultural practices. Tillage practices were chiefly those borrowed from more humid sections, and there was no uniformity of opinion regarding the ones that should be used or, in fact, whether the area should be farmed at all. Each wave of settlement had left a remnant of scattered farmers who adapted themselves to the area and made a living, most frequently by a combination of farming and livestock production. The last great wave of settlement, prior to the turn of the century, was in the late 1880's, when most of western Kansas and much of eastern Colorado was homesteaded. More favorable rainfall in the late 1890's and in the early years of the twentieth century induced another great wave of settlement that proved to be relatively permanent. Most of the remaining arable land in the Great Plains was settled by farmers during the period from the late 1890's to 1915.

The tillage implements available in the United States at the end of the century were chiefly the moldboard plow, disk harrow, and spike-tooth harrow. Disk plows were used in some heavy sticky soils but were not popular. The lister was also used somewhat as a tillage implement for wheat in the central and southern Plains region. The spring-tooth

harrow, subsoilers, and spring-tooth cultivators were just beginning to assume prominence. Knife implements, generally homemade, were coming into use for the maintenance of fallow. But the choice of implements available to the individual farmer was very limited.

2. Improved Practices in the Eastern States

In the eastern United States wheat was grown almost exclusively in rotation with other crops, and cultural practices for wheat depended as much on these crops as on the needs of the wheat itself. Much wheat was grown after corn and was either seeded in the standing corn or on disked land after the corn was removed or shocked. Where wheat followed oats the land was generally plowed, and the desirability of plowing far enough in advance of seeding to provide a well-settled weed-free seedbed was recognized at an early date. Timing of the operation was usually fixed by the labor required on other crops. Much the same is true today, although in recent years great improvement has been effected by the speeding up of all farming operations through mechanization, permitting work on all crops to be done at nearer the optimum time.

Since the beginning of the twentieth century, wheat yields have been increased by the use of more small-seeded legumes in rotations, and by allowing legume or grass–legume mixtures to occupy the land for more than one year. These longer rotations reduce the total acreage of wheat but improve the acre yield.

Extensive date-of-seeding tests throughout the area have been most useful. Seeding dates that will avoid serious damage by the Hessian fly in most cases have been worked out by entomologists for all of the principal wheat-growing states (Call *et al.,* 1916; Baker and Mathews, 1952). Delays much later than the fly-free dates often result in reduced yields. Mechanization of farm operations has speeded land preparation and seeding so that most wheat can be sown on well-prepared seedbeds late enough to avoid fly injury but within the period when optimum yields can be obtained. Rates of seeding wheat were fairly well worked out through experiments many years ago, and improvements through adjusted rates have been minor.

The last to be mentioned but not the least important means of improving wheat yields in the Eastern States has been through increased use of lime and fertilizers. Wheat benefits from the fertilizer applied to it directly, and also from the residual effects of fertilizers applied to other crops in the rotation. Nearly every state is conducting experiments both on quantities to use and on the time and method of application on all of the principal soil types and within the principal climatic zones within its borders. The quantity that can be profitably applied

depends partly on the relationship between the price received for wheat and the cost of fertilizer. A relatively favorable price relationship in recent years has encouraged use at higher rates than previously, but the limit of profitable application to the wheat crop of the Eastern States as a whole has not yet been reached.

3. *Improved Practices in the Far West*

The major improvements in practices in the Far West have consisted in better methods of handling fallow, substitution of other crops for fallow in limited areas where the yearly rainfall permits the profitable growing of legumes in rotation with wheat, and the use of more fertilizers.

a. Methods of Preparing Fallow. Improvements in the methods of preparing fallow and in maintaining the fallow have been especially important. Although there was an extensive background of farmer experience in handling fallow, experimental evidence relating to the relative advantages of the different systems that were advocated or to the reasons were lacking until near the end of the second decade of the present century.

In the absence of reliable information, early recommendations by the state experiment stations were made on the basis of farm experience and of what seemed to be reasonable. As is usual in such circumstances, however, there were many differences of opinion, and recommendations often disregarded the conditions to which they were to be applied. Disking soon after harvest and plowing in the fall were almost universally recommended. Maintenance of a mulch throughout the summer that the land was in fallow was also recommended, but the danger of leaving the soil too fine soon was recognized (Severance, 1909). Such implements as the knife cultivator and the gooseneck slicker, which killed weeds without pulverizing the surface, were developed early. There was also some recognition of the fact that cultivation sufficient to kill weeds was all that was required, and that special practices were necessary on land subject to blowing.

Enough experimental results from dry-land stations in Oregon, Washington, and Utah had accumulated by the early twenties so that dependable information was available (Stephens *et al.*, 1923, 1932). The results from different locations were remarkably uniform in indicating no benefit from any tillage, regardless of type, beginning the year that the crop was harvested. But preparation early in the spring of the fallow year is imperative if maximum yields are to be obtained. Typical results reported by Stephens *et al.* (1923) and by Hunter (1927), showing the effect of time of plowing at three stations, are presented in Table I.

TABLE I

Effect of Time of Plowing for Fallow on Yields of Wheat at Three Stations in Oregon, Washington, and Utah

Station and time of plowing	Average yield, bu./acre
Moro, Oregon, 1914–1925	
Fall plowing	
Dry in early fall	27.2
Wet in late fall	24.2
Spring plowing	
April 1	30.4
May 1	28.0
June 1	23.1
Lind, Washington, 1918–1925	
Fall plowing	
Dry in September	9.9
Wet in November	10.5
Spring plowing	
March 1–10	12.4
April 10–20	12.0
May 20–21	9.5
Nephi, Utah, 1916–1921	
Fall plowing	
About October 10	24.5
Spring plowing	
Early	24.2
When volunteer plants were 6 in. high	20.9
When volunteer plants were in early bloom	16.9

In all cases the land was kept free of weeds by cultivation after plowing. The results emphasize the drastic reduction in yield that results when fallow operations were not started until late May or early June. It also was found that plowing could be delayed considerably without serious reduction in yield if the land was disked or otherwise cultivated in the early spring. Harrowing or packing the land after early plowing did not increase yields but was beneficial if the plowing was done late. Many other practices were tried but on land where fallow operations were started early, it soon became evident that cultivations beyond those required to control weeds during the summer and to create a firm seedbed were unnecessary. Although the depth factor was not emphasized so strongly as in some other sections, deep plowing frequently was urged. Experimental results, however, usually have indicated no benefit from

plowing to depths in excess of 7 or 8 inches. Shallow plowing has resulted in slightly lower yields at a few locations. This may be related to nitrate formation prior to seeding, but this has not been definitely proved. Not the least of the benefits derived from these experiments was the material reduction in the cost and number of operations, since deep plowing is relatively expensive and since, because of the nearly rainless summers, very few cultivations are required to control weeds.

Hunter (1927) summarized the situation as follows: "A comparative study of the tillage methods practiced and the yields obtained on individual farms in various dry-farming localities leads definitely to the conclusion that the acre yield of wheat can be increased materially on many farms by changing the method of summer fallowing. In the main, these changes would be effected by doing the tillage work at the time it would be most effective."

b. Disposition of Heavy Stubble. The disposition of the heavy stubble after harvest has always been a serious problem for the wheat–fallow farmer and especially so since the advent of the combine. There was a time when most of the stubble was burned, either for convenience in operations, or, as in the higher rainfall portions of the fallow area, because leaving the stubble on the land decreased yields. Increasing recognition of the value of the stubble for erosion control and soil maintenance, coupled with fertility practices that improve yields on straw-mulched land, has greatly reduced stubble burning, although many details regarding the best methods of handling crop residues remain to be worked out.

c. Use of Fertilizers. The use of fertilizers, particularly nitrogen, has been responsible for material improvement in wheat yields in certain areas, especially in those with a relatively high rainfall. The situation in the wheat belt of Washington, Oregon, and northern Idaho may be summed up about as follows: Nitrogen is beneficial on most soils unless moisture is the limiting factor. Moisture is usually the chief limiting factor in areas of less than 12 inches of annual precipitation, and frequently in areas with 12–14 inches of precipitation. Results from the use of nitrogen in these areas are variable and usually not profitable. In areas with 14–18 inches of average annual rainfall and where wheat is grown on fallow, the use of nitrogen permits retaining the straw on the surface for erosion control without depressing the yield. Nitrogen may also increase yields on what is usually termed "black fallow." Applications of nitrogen to wheat on fallow have generally been unprofitable in areas with more than 18 inches of rain. Where wheat is grown each year, as it sometimes is in the higher rainfall belt of the Pacific Northwest, nitrogen applications have raised yields to a level that may

make fallowing unnecessary. Much of the land in the 18- to 20-inch rainfall belt is now planted to alternate wheat and peas. Profitable increases in yield of wheat on pea land have been obtained from applications of nitrogen in most years in low rainfall areas. Much remains to be done, especially to determine the best use of fertilizers under different soil, climatic, and crop residue conditions. Increases in yield due to applications of phosphorus have not been numerous, but occur on certain soils in some states. As yet phosphate applications have been of very minor significance in influencing wheat production.

d. Legumes in Rotation with Wheat. Legumes other than peas such as alfalfa and sweetclover are grown in wheat rotations to some extent, particularly in the 20-inch rainfall area (Baker and Klages, 1938). The yield of wheat immediately after such crops frequently is reduced by excessive nitrates if the season is dry, but they leave a beneficial residual effect that is evident for several years.

4. Improved Practices in the Great Plains

The Great Plains, where much of the nation's wheat crop is now grown, was originally defined as an area extending from the Canadian line to central Texas, bordered on the east by the 98th parallel of longitude and on the west by the 5,000-foot elevation contour along the eastern edge of the Rocky Mountains. These boundaries are arbitrary and for the purposes of this discussion, the eastern portions of the States of North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma are considered part of the area. In general, the elevation rises and the precipitation diminishes from east to west.

The drier portions of the Great Plains were settled chiefly by farmers and others from wetter areas, most of whom, in the absence of dependable information adapted to the area, continued to use the crops and tillage practices of the area from whence they came. The state experiment stations were located either along the eastern higher-rainfall fringe or in irrigated valleys, where most of the agriculture was concentrated, and experimental results applicable to the drier areas were not available. The experience of successful established farmers was available to only a few.

Although factual information was almost completely lacking, pseudoscientific information and propaganda were not. The term "dry farming," brought into general use during the early years of the present century, was a word to conjure with and feature editorials on dry farming appeared in daily papers and farm magazines throughout the country. Dry farming was represented as a magic formula for producing crops on little water through a system of thorough cultivation. Crop

production was to be made safe by the combined miracles of "capillarity" and the "dust mulch." The dust mulch was to prevent water loss from the soil through evaporation, and capillarity was to bring stored water from below up to the crop roots. There was no concept of the actual quantities of water required to produce crops or of the water that could be absorbed by, and held in, the soil. The more conservative element spoke of saving 50 per cent of the summer rainfall; the optimists regarded 90–95 per cent as an attainable figure. Even the conservative estimate now seems fantastically high (Thysell, 1938; Zook and Weakley, 1944).

The optimistic outlook on Plains agriculture was accentuated by a general belief that the climate was changing. Such expressions as "rainfall follows the plow" were repeated not only by those who believed in them but by those who had a financial interest in getting settlers into the area. The fact that the period from 1895 to 1910 was one of above-average rainfall for most of the Plains area added credence to the statement. It is hard at this time to appreciate the optimistic atmosphere that prevailed in the Plains during the early years of the century.

A number of men voiced practical objections to many of the benefits claimed for "scientific dry farming," but the number was few, and the opposition so vociferous that they were able to gain little attention. Those who advised caution were handicapped by the fact that they had absolutely no data except from the extreme eastern edge of the dry-land area on which to base their opinions, and objections to the prevailing opinion were likely to be ascribed to ignorance or viciousness. As late as the early years of the second decade of the century, a Department official was ridiculed and abused in his home state for making the statement that the climate was not changing.

A name inseparably associated with dry farming is Hardy W. Campbell, who became widely known as the originator of the "Campbell System" of dry farming. Although many of his ideas were faulty, his system embraced enough essentials of good farming that those practicing it could be expected to fare better than the average. He recommended the alternate wheat–fallow system and cultivation after every rain. He also emphasized the role of capillarity in supplying water to crops, but he recognized the dangers of a finely pulverized soil that would blow and recommended cultivation practices that would leave fine clods rather than a dust mulch on the surface.

Like many others of his time, he overestimated the importance of frequent cultivation and underestimated the difficulties of maintaining a soil mulch that would not blow. Hazen (1908) summarized the situation in a few words as follows: "There has been much written on how

to establish a soil mulch but so far there is little information on how to keep it.''

a. Early Experiments in Dry-Land Agriculture. In 1905 Secretary of Agriculture James Wilson established the beginning of a dry-land agricultural research program. E. C. Chilcott was appointed to direct the work and Lyman J. Briggs to assist him. They established cooperative relations with the states and started work in 1906 at all of the six branch stations then established in the Great Plains area. This was later extended to about twenty-five stations, although all were not in operation at one time. Many of the experiments were conducted simultaneously at all stations that grew the same crops in order to develop principles that would have a regional application.

The early results of these tillage experiments were largely negative, since they did little more than point out the fallacies of many of the practices then being advocated. This was no mean accomplishment, since the theories of dry farming were deeply rooted and were supported by many vested interests, if not by experimental evidence. A few of the principal misconceptions are discussed in the following paragraphs.

1. The dust mulch. Perhaps the most important of these was the theory of the dust mulch. According to prevailing beliefs, a dust mulch prevented evaporation and retained the water that was in the soil and at the same time permitted water to penetrate into the soil and increase the stored supply. The classic laboratory experiments of King in Wisconsin, in which it was shown that water would rise in a glass tube filled with soil in contact with water in a pan, were accepted by laymen and scientists alike as positive proof. Coupled with this was the belief that plant roots penetrated little or not at all below the plowed surface and that capillarity brought water to the roots from the lower depths. As we now know, roots go where there is moisture, and capillary movement of water is exceedingly slow and confined to very short distances. It exerts as much force in moving water downward as upward in a soil without a water table, as in the drier Plains. It was not, however, until about 1915 that the accumulation of data from soil moisture studies as reported by Burr (1914), Grace (1915), Mathews and Chilcott (1923), and Call and Sewell (1917) were sufficient to support these conclusions.

2. Deep plowing and subsoiling. The theory that deep plowing and subsoiling were necessary in order to assure water penetration and storage and a deep layer of soil in which plant roots could grow seemed to have a strange fascination. There were no experimental data to support this belief, but it was a beguiling theory. Interesting in retrospect is the fact that a few experiments had shown no advantages whatever for deep plowing and subsoiling as compared with ordinary plowing. For-

tunately, few farmers actually plowed deep or subsoiled, either because they lacked the power and equipment to do so or because they questioned the soundness of the idea. Actually it required only a few years of experimental work completely to demolish the theory of deep plowing and subsoiling. They were summarized by Chilcott and Cole (1918) as follows: "Subsoiling and deep tillage have been of no benefit in overcoming drought." More recent results reported by Volk (1947) also indicate no benefit from subsoiling for small grains.

b. Early versus Late Tillage for Winter Wheat. Although the first important results from tillage experiments consisted largely in discredit-

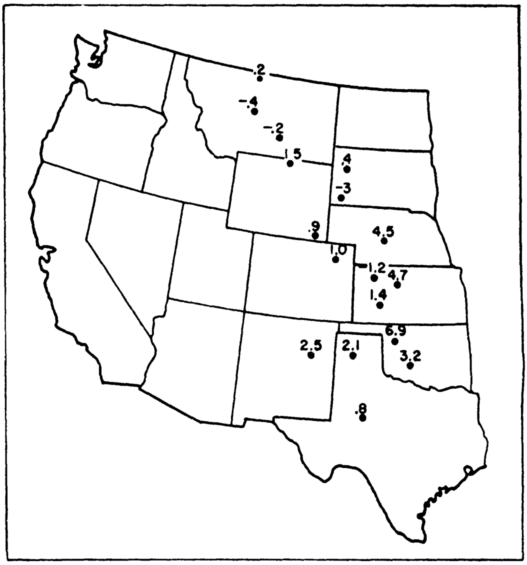

FIG. 11. Average gain in bushels per acre of early over late tillage for winter wheat in experiments in the Great Plains. Averages are for periods of from ten to forty-two years.

ing much of the prevailing theory, positive achievements soon followed. Among the more important of these were the verification of results obtained in more humid areas that indicated a material advantage for preparing the ground for wheat as soon as possible after harvest. Perhaps even more important was finding where, why, and under what conditions these advantages could be expected. These early experiments principally at Stillwater, Oklahoma, (Moorhouse, 1908) and Manhattan, Kansas, (Call, 1913; Salmon and Throckmorton, 1929) had indicated an average gain for early plowing as compared with late plowing of the order of 5 bushels per acre. More recent and extensive experiments

which are summarized in Fig. 11 indicate an average gain of about 5 bushels per acre at Woodward, Oklahoma, Hays, Kansas, and North Platte, Nebraska, but considerably less at other locations.

The reasons why early tillage did not always accomplish the expected results became evident as time went on. Early plowing is known to permit the storage of a portion of the rainfall between harvest and seeding and to provide conditions favorable to nitrate formation. How these two factors operate in determining yields may be illustrated by results from the three stations in central and western Kansas. At Hays, in the central part of the state, considerably more moisture is stored by early tillage than by late tillage and moisture sufficient to utilize the nitrate produced by early tillage is usually present. At Colby and Garden City in western Kansas, with less precipitation and consequently less stored moisture, especially between harvest and seeding, the excess nitrates provided by early tillage are as likely to be injurious as they are helpful. If moisture is plentiful, early plowing produces the higher yield. If not, the better early growth on early plowed land results in more serious drought injury and a lower final yield. Hallsted and Mathews (1936) found that it required a season of summer fallow at Colby and Garden City to provide moisture enough so that crop prospects were comparable with those under early tillage at Hays.

Although average results in the western portion of the Plains do not favor early tillage by a wide margin, tillage shortly after harvest may be advisable in some years. If rains shortly before or immediately after harvest have left considerable moisture in the soil that may be dissipated by weeds, prompt tillage is usually highly beneficial.

c. Experiments with New Tillage Implements. Implements that covered the ground more rapidly and at less expense than the plow began to appear in numbers after 1915, some accompanied by rather extravagant claims as to their effectiveness. The first really comprehensive tests of the use of a wide variety of such implements in seedbed preparation were started at Hays, Kansas, in 1919 and expanded during the next few years. These were conducted on land where wheat was grown each year and consisted not only of comparisons of the principal implements then available but also of early and late tillage with the same implement. The methods included chiseling to depths of 6 inches and 12 inches, duckfooting, plowing, listing, and one-waying wheat stubble; and plowing, listing, and one-waying land where the stubble had been burned. Chiseling consists of tilling the soil with an implement with a curved pointed shank and very narrow shovels that break up the soil but do not invert it. The difference between early and late tillage was pronounced, but yields from early tillage performed with different implements were re-

markably uniform. This indicated that neither the depth of tillage nor the disposal of the crop residue had any great influence on yields. The different implements varied greatly, however, in their costs of operation, in the subsequent cultivation required, and in the resistance to erosion of the soil surface resulting from their use. Similar results have been obtained at other locations, and emphasize that choice of implements may be dictated by factors other than yield. These results are not universal, but the exceptions are usually due to specific causes that can be identified.

The use of implements that cover the ground more quickly and with less expense than the plow without impairment of yields has greatly reduced the costs of growing wheat and has insured greater timeliness in seedbed preparation and seeding.

d. Fallow in the Great Plains. Some wheat was grown on fallow in the more arid sections of the Plains at the beginning of the century, but the practice was slow in becoming established partly because farmers were loathe to believe that they could not grow a crop every year. Also, frequent cultivation with a disk or harrow greatly encouraged soil blowing. Fallowing was not as complete an insurance against crop failure as many believed or to the extent that it was on the semiarid lands of the Far West. In a very severe drought, wheat on fallowed as well as on cropped land might be a complete failure. Chilcott compared fallowing to fire insurance that afforded protection against small fires but not against a general conflagration.

TABLE II

Estimated Acreage in Summer Fallow for Selected States and Periods

Period	Seven Western States,* millions of acres	Ten Great Plains States,† millions of acres	Total seventeen states, millions of acres
1928–1932	5.5	5.3	10.8
1939	5.4	15.9	21.3
1942	5.4	14.4	19.8
1943	5.1	12.0	17.1
1944	4.6	10.2	14.8
1951 ††	5.6	17.9	23.5

* Washington, Oregon, Idaho, California, Nevada, Utah, and Arizona.

† Montana, Colorado, Wyoming, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas.

†† Data for 1951 from "Agricultural Capacity to Produce," *U.S. Dept. Agr. Inform. Bull.* 88, June 1952.

Interest in fallow began to increase in the twenties and was especially great during the drought in the mid-thirties. The extent to which fallow has been used at various times in seven Western States and in the ten states of the Great Plains, as reported by Johnson (1949), is shown in Table II.

The greater portion of fallowed land in the United States is sown to winter wheat, which shows more response to fallow than do most other crops. Spring wheat also is grown on fallow, chiefly in the northern and drier portion of the Great Plains spring wheat area and to a lesser extent in the Columbia River basin, particularly in years when conditions are not favorable at winter wheat seeding time.

Yields of spring and winter wheat on fallow and on stubble land at stations through the Great Plains, as summarized by Mathews (1951), are given in Table III. Results from five locations in the dry-land portion of the Western States are also included for comparison. In this table summer fallow is compared with wheat following small grain with good tillage methods. Neither the fallowed nor the annually cropped land received any soil amendment.

It will be noted that the increases in yield per acre of wheat on fallowed land as compared with stubble land are about as great in the central part of the Plains as in the drier portions. In the more humid areas the yields on cropped land are much higher than in the western areas, however, which reduces the need for fallow. In these areas a rotation including corn or some other cultivated crop is generally more profitable than alternate wheat and fallow.

TABLE III

Acre Yields of Wheat after Fallow and Small Grain Stubble at Locations in the Great Plains and in the Drier Portion of the Western States

State and location		Years	Spring or winter wheat	Wheat yield, bu./acre	
				Fallowed land	Stubble land
Western States					
Oregon:	Moro	1912–1950	Spring	23.8	12.5
	Pendleton	1931–1950	Winter	41.7	14.1
	Pendleton	1931–1950	Spring	42.2	15.0
Idaho:	Tetonia	1940–1949	Winter	24.4	11.3
Utah:	Nephi	1904–1945	Winter	23.4	10.0
Great Plains					
Montana:	Havre	1917–1950	Winter	12.1	4.3
	Havre	1917–1950	Spring	14.8	8.9

TABLE III—*Continued*

State and location		Years	Spring or winter wheat	Wheat yield, bu./acre Fallowed land	Stubble land
	Moccasin	1910–1950	Winter	18.1	8.6
	Moccasin	1910–1950	Spring	17.3	13.0
	Huntley	1915–1950	Winter	22.4	9.0
	Huntley	1915–1950	Spring	16.8	9.4
North Dakota:					
	Edgeley	1941–1945	Spring	29.3	21.4
	Langdon	1941–1945	Spring	31.3	18.4
	Mandan	1915–1950	Spring	21.9	14.9
	Dickinson	1908–1950	Spring	20.8	13.2
	Hettinger	1912–1922	Spring	16.9	11.5
	Williston	1910–1920	Spring	18.6	12.1
South Dakota:					
	Highmore	1912–1930	Spring	15.9	9.9
	Belle Fourche	1909–1949	Winter	21.9	13.3
	Belle Fourche	1909–1949	Spring	21.8	13.9
	Ardmore	1913–1932	Winter	18.4	8.9
	Ardmore	1913–1932	Spring	19.1	12.6
Wyoming:	Sheridan	1918–1950	Winter	31.0	16.2
	Sheridan	1918–1950	Spring	24.7	14.8
	Archer	1914–1948	Winter	14.1	7.4
	Archer	1914–1948	Spring	12.8	7.4
Nebraska:	North Platte	1936–1950	Winter	26.5	14.0
	North Platte	1936–1950	Spring	12.1	8.1
	Scottsbluff	1912–1921	Winter	18.5	7.6
	Scottsbluff	1912–1921	Spring	16.0	8.5
	Alliance	1931–1950	Winter	18.1	8.5
Colorado:	Akron	1909–1949	Winter	17.8	7.6
	Akron	1909–1949	Spring	11.4	6.9
Kansas:	Hays	1908–1945	Winter	22.5	16.4
	Hays	1908–1945	Spring	9.5	6.4
	Colby	1915–1950	Winter	17.6	8.9
	Colby	1915–1950	Spring	8.4	5.4
	Garden City	1912–1947	Winter	16.6	8.5
Oklahoma:					
	Woodward Field A	1915–1948	Winter	22.2	17.3
	Woodward Field B	1933–1948	Winter	25.1	18.9
	Lawton	1924–1948	Winter	21.2	15.9
	Goodwell	1926–1935	Winter	13.9	8.8
Texas:	Big Spring	1917–1949	Winter	5.3	5.1
	Dalhart	1927–1949	Winter	10.0	6.5
	Amarillo (BPI)	1907–1919	Winter	10.7	9.0
	Amarillo (SCS)	1942–1949	Winter	23.2	14.0
New Mexico:					
	Tucumcari	1930–1940	Winter	10.5	5.5

(*1*) *Methods of handling fallow.* Experiments in methods of preparing land for fallow have given substantially the same results as in the Western States so far as principles are concerned and with only minor differences as to their application. Plowing immediately after harvest has proved no better than, and seldom as good as, plowing late in the fall. At only one location has fall tillage been better than leaving the stubble undisturbed until mid-May. Leaving the stubble undisturbed until mid-June has reduced the yield markedly, usually 3 or 4 bushels to the acre.

Perhaps the most important achievement is the development of implements that cover land more rapidly and the great reduction in the number of operations believed to be necessary. This can be illustrated by a comparison of the number of cultivations during the fallow periods in experiments conducted during the early years, when frequent cultivation was believed to be necessary, with those conducted at a later period, in which the fallow was cultivated only as necessary to control weeds or establish a good seedbed. At Hays, Kansas, for example, where summer rains are more frequent than at most Great Plains stations and where those in charge were meticulous in following recommendations, the number of separate tillage operations for the entire fallow period in the early years sometimes exceeded twenty-five. At other locations the number ranged from as few as ten up to fifteen or more. These may be contrasted with those in experiments begun at Colby, Kansas, in 1922, in which the fallow was cultivated only as necessary to control weeds and establish a good seedbed. Table IV gives the results at Colby, including the length of the fallow periods, the number of cultivations, and the average yields for fallow first plowed at different dates.

TABLE IV

Length of Fallow Period and Number of Tillage Operations Required to Establish and Maintain a Fallow and Average Yields on Fallow Initiated at Four Different times, Colby, Kansas, 1922–1950

Average date of first plowing	Length of fallow period, months	Number of tillage operations		Comparative yield, bu./acre
		Plowing	Surface tillage	
July 25	14	2	4	16.6
October 30	11	1	4	18.0
May 17	4	1	3—	18.0
June 17	3	1	2	14.3

The best time to begin the fallow appears to be about the middle of May. Plowing late the preceding fall was equally effective, but plowing

soon after harvest the preceding summer gave slightly lower yields. Delaying the plowing until about the middle of June reduced yields materially. Starting the fallow May 17 required that the land lie in fallow for only about 4 months. This reduced the number of cultivations after plowing to less than three and greatly reduced the opportunity for soil blowing, as compared, for example, with plowing the previous summer followed by cultivation after every rain.

(2) *Control of soil blowing.* Although soil blowing is especially serious on finely pulverized soil, such as that produced by frequent cultivation, the best of the cultural practices known up until a few years ago are not fully effective with such severe and widespread drought as that of the early thirties. Severe dust storms of this period that sometimes carried dust to the Atlantic seaboard focused national attention on the need for control. It had long been evident that a soil with clods or crop residues on the surface was least subject to soil blowing. As long as the plow, disk, and harrow were the only implements used for land preparation and cultivation, improvement in control methods was difficult and slow. Regardless of intentions, the tillage necessary to kill weeds might render the soil fine enough to mellow down during the winter and be in condition to move easily in the spring. Even large clods may break down during the winter.

Summer fallow presented the worst hazard of soil blowing, and it was in summer fallow areas that equipment designed to replace regular plowing or to lessen the bad effect of subsequent cultivation first originated.

The moldboardless plow and Noble blade were two implements designed to make regular plowing unnecessary. Implements designed for subsequent cultivation that left residues or clods on the surface were the knife slicker, duckfoot or field cultivator, spring-tooth harrow, and rod weeder. The duckfoot was at first used for cultivations after plowing. Later it was found that it could be used on stubble land to replace plowing as the first operation in fallowing.

Implements such as the oneway, lister, and chisel first came into prominence not as implements for prevention of soil blowing but as cheaper methods for the first operation of preparing a seedbed. They were used chiefly where wheat was grown each year, but also in fallow operations. The oneway in particular came into vogue in the central and southern Plains and almost displaced other equipment. It covered ground rapidly and was efficient in killing weeds. It pulverized the soil considerably, but no great harm resulted as long as there was considerable stubble residue left in the surface soil, or when moisture was sufficient to produce a good fall growth of wheat. It required a year of scant

residues, together with a fall so dry that wheat either did not emerge or made very little fall growth, to point out the injury it was capable of doing. The repeated use of this implement on soils with scanty residues was largely responsible for the extensive soil blowing in central and southern winter wheat regions in the mid-thirties. The oneway is still recognized as one of the best implements for wheat tillage, but its limitations are better appreciated. It can be used once or even twice on heavy stubble without danger, but when there is little crop residue on the surface or if it is used repeatedly, it is likely to promote serious blowing.

(3) *Strip fallow.* A practice known as strip fallowing, that probably originated in Canada and spread to adjacent Plains states, has proved to be one of the most effective advances in methods to prevent soil blowing in a system of farming that includes fallow. In this system, wheat and fallow are arranged in alternate long narrow strips ranging in width from 5 to 20 rods. The greater the danger of blowing, the narrower the strips should be. The strip in stubble traps any soil that may move from the fallowed land during the winter or early spring, and prevents soil movement from gaining much headway. The lower limit for width of strips is generally placed at about 5 rods, since it is felt that land that cannot be safely handled in strips of this width should not be fallowed. One objection to strip fallowing in the extreme northern Plains of the United States and in adjoining portions of Canada is damage from wheat-stem sawfly, believed to be favored by the adjacent strips of growing wheat and infested stubble.

The grasshopper problem is frequently increased when winter wheat is planted adjacent to a strip left untilled for fallow the following year. This can be offset in part in the portion of the Plains where sorghum also responds strongly to fallow by placing the wheat strips adjacent to sorghum. Such a set-up is possible with two alternate crop–fallow systems, i.e., wheat–fallow and sorghum–fallow.

(4) *Stubble mulching.* A practice known as stubble mulching came into prominence in the late thirties and early forties, both as a preventive of soil blowing and as a moisture-conservation measure. Although used mostly in connection with fallow, it is not restricted to systems of farming including fallow. The terms "stubble mulch" and "subsurface tillage" were at one time considered synonymous. The term stubble mulch has been expanded to include any type of cultivation that leaves enough residue on the surface to protect it from erosion, regardless of the type of implement used. Early results reported by Duley and Russel (1939) showed that a straw mulch was highly effective in storing moisture under conditions prevailing at Lincoln, Nebraska, and it was assumed that it would be of even more value in the dry-land section, where conservation

of moisture is of paramount importance. It was a logical assumption that leaving all crop residues on the surface would result in material increases in moisture storage, since it had been shown that such residues protect the surface from the sealing effect of raindrops striking the soil directly, and reduce runoff slightly.

That the stubble mulch has not increased moisture storage in experimental trials in dry-land areas is one of the anomalies of nature. It has not done so during a season of fallow or particularly during the period between midsummer harvest and fall seeding in the winter-wheat area of the central and southern Plains. It appears to contribute most to moisture storage in areas of heavier precipitation where such storage is less important. It has increased the yield in some dry-land areas, but such differences can be ascribed to factors other than moisture storage.

A stubble mulch on the surface reduces the quantity of nitrate nitrogen in the surface soil below that present on plowed land (Scott, 1921; Albrecht, 1926; McCalla and Russel, 1943; Sewell and Call, 1925). This may be harmful or helpful, depending on other conditions. At Pendleton, Oregon, where the stubble is heavy and the soil somewhat deficient in nitrogen, yields of wheat on stubble-mulch fallow have been several bushels per acre lower than those on plowed land. No such reduction has occurred in drier areas of the Pacific Northwest, and no reduction from its use on fallowed land has been found in the Great Plains, where lack of nitrate nitrogen is seldom a controlling factor.

The use of a stubble mulch in a nonfallow system of farming depends on other factors as well as nitrate nitrogen. In the southern Great Plains yields of wheat have been increased by use of the stubble mulch at Amarillo, Texas (Johnson, 1950). In that area moisture is more of a limiting factor than nitrogen, and the smaller growth on mulched land due to lack of nitrate nitrogen at seeding time has resulted in an increase in grain yield over that from plowed land. The difference has been greatest in years of relatively low yields. Plowed land has always produced the greater straw growth and in favorable seasons may produce the higher grain yield. At Cherokee, Oklahoma, as reported by Daniel *et al.* (1951), yields on stubble-mulched land have been materially below those on plowed land. The difference has been ascribed to poorer weed control and to a limited extent to disease and insect factors. Results similar to those at Cherokee have been obtained at Manhattan, Kansas. At practically all other locations in the Great Plains, stubble mulching has neither increased nor decreased winter wheat yields.

In the spring-wheat area, stubble mulching has generally decreased yields (Aasheim, 1949; Engelhorn, 1946), probably owing to poorer weed control. This type of cultivation leaves most of the weed seeds on the

surface, where they can germinate promptly and be in position to compete with the crop.

Stubble mulching has had little place in wheat production in the east central and eastern United States, since wheat is not generally grown following a crop that leaves a heavy residue. Also, control of weeds in a stubble-mulch system is more difficult in humid areas than in dry areas. Results as a whole have not been favorable to mulch tillage for wheat, owing both to poorer weed control and to less ready availability of plant nutrients. Up to the present time it has played no part in wheat production east of the Great Plains states.

The stubble mulch has been of great value as a safety factor in the Great Plains. It has made fallow much more stable and permitted its use in sections that would otherwise have been questionable. In the area where winter wheat is grown annually, a properly maintained stubble mulch may make it possible for a crop that has made a poor fall growth to survive the spring blow period without damage. The value of a stubble mulch can be accredited almost entirely to protection against wind and water erosion. Protection from wind erosion may be of immediate benefit, but the value of protection from water erosion lies chiefly in preventing loss of soil that would impair future productivity.

(5) *Stubble mulch implements.* Implements created especially for stubble-mulch tillage have been important in putting stubble mulching on a practical basis. They are of different types, but the general principle is the same. They are designed to operate parallel with the surface and to undercut all the land with the least disturbance of surface residues consistent with weed control and the preparation of a suitable seedbed. The main types are machines with sweeps, sometimes attached to plow or lister frames or to tool bars on tractors. The Graham-Hoeme plow, now widely used, is essentially a chisel with small detachable sweeps. The Noble blade, a straight-blade undercutting implement, is widely used in the northern Great Plains for the first operation on land being fallowed. The straight blade can be replaced by wide sweeps for subsequent tillage operations. The leading implements for subtillage, especially in heavy stubble, are the oneway followed by the rod weeder. The oneway reduces the quantity of stubble to manageable proportions and the rod weeder controls weeds and firms the seedbed. The rod weeder was not designed originally for stubble mulches, but it is invaluable in many places for tillage subsequent to the initial stirring of stubble land. It eliminates weeds while keeping residue and clods on the surface. Used at a shallow depth shortly before seeding, it compacts the soil and assists in making a firm seedbed.

The common purpose of subtillage implements is to kill weeds and

other unwanted vegetation and at the same time maintain enough residue on the surface to prevent erosion and to facilitate penetration of water. Any modification through interchange with other implements is permissible as long as it does not conflict with the general purpose.

e. Fall versus Spring Plowing for Spring Wheat. Fall plowing of stubble land for spring wheat has long been accepted as good practice in the eastern Dakotas, and the reasons on which this view was based were sound. Walster (1920a) quotes results from Fargo obtained late in the nineteenth and early in the twentieth century that showed an advantage of about 2 bushels to the acre in favor of fall plowing. Advantages other

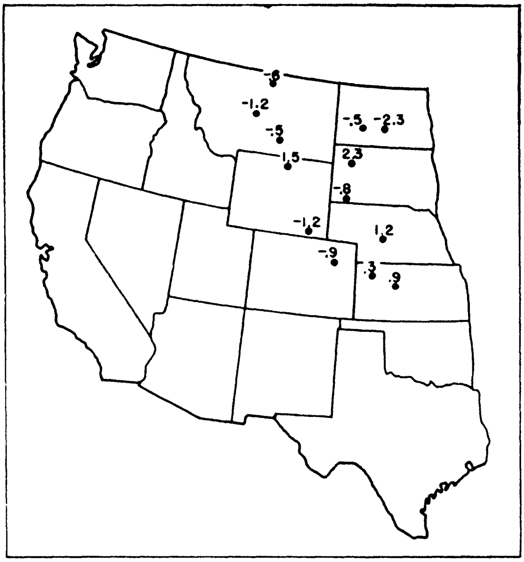

FIG. 12. Average gain in bushels per acre of early fall over early spring plowing in experiments with spring wheat in the central and northern Great Plains.

than yield were that it afforded a better distribution of labor, insured the land being in condition for early seeding, checked weed growth after harvest, and buried grasshopper eggs. Early seeding may have been partly responsible for the difference in yield he reported, since land prepared by each method was seeded when it was ready, meaning ordinarily that land prepared in the fall would be seeded earlier in the spring than land plowed in the spring.

The results of more recent and extensive experiments in the drier portions of the central and northern Plains are shown in Fig. 12. In these seeding was at the same time in the spring regardless of time of

plowing. The fall plowing was done at various times from soon after harvest to late fall.

These results indicate little or no benefit from plowing in the late summer or fall. The average yield from fall plowing was higher than that from spring plowing at only two stations. At both of these the nature of the soil is such that in many years a suitable seedbed on spring-plowed land could not be prepared. The generally better yield obtained on spring-plowed land is probably related to the moisture content of the soil. Thysell (1938) found at Mandan, North Dakota, that the land left in stubble over winter contained an average of nearly 2 inches more water than fall-plowed land, owing probably to the snow caught by the stubble. Even in dry areas where fall plowing seems desirable, it is often not practical because the soil is so dry and hard in the summer and fall that plowing is difficult and expensive. Walster (1920a) summed up the situation as follows: "For western North Dakota the time of plowing may be adjusted to suit the convenience of the farmer and the amount of moisture in the soil."

f. Depth and Kind of Tillage for Spring Wheat. Tests of depth of plowing small-grain land for spring wheat have been conducted at comparatively few locations. Results in general have slightly favored 6- to 8-inch over very shallow plowing, but the difference has been too small to more than offset the difference in cost.

Tillage operations for spring wheat have been greatly facilitated by the development of new implements and by the advent of the tractor, the oneway, and the chisel. They are now frequently used in place of the plow, and adequate power has made it much more nearly possible to plow or otherwise till the land in the spring and still get the seeding done at a suitable time. A relatively new development in spring plowing that may increase its use is combinations of implements consisting of multiple-bottom plows followed by those that work down the soil and seed in a single operation. This does away with the delay incident to working down and seeding spring-plowed land, and puts the seed in moist soil where it can germinate promptly and compete with weeds on favorable terms.

g. Time and Rate of Seeding Wheat. Rate-of-seeding experiments for both winter and spring wheat show that there is no rate that is outstandingly better than others. Rates of from 4 to 8 pecks per acre have shown little difference in net yield. Spring wheat seeded at a rate much lower than 4 pecks per acre is likely to suffer more from weed competition than thicker stands. Winter wheat in the western part of the Plains can be seeded on clean firm moist seedbeds at the rate of 2 pecks per acre, or sometimes less, without material reduction in yield. There is consider-

able evidence (Salmon and Throckmorton, 1929) that the planting rate of winter wheat seeded late should be somewhat higher than that for early seeding.

The optimum time for seeding winter wheat in the Eastern States, including the more humid portions of the Great Plains, is determined to a considerable extent by prospective damage from Hessian fly, as will be discussed later. In the drier western Plains, where Hessian fly is seldom a factor, there is remarkably little difference at locations ranging from northern Montana to southern Oklahoma. There is usually a period of about a month from about the middle of September to the middle of October when average yields vary so little that other factors may determine the best time to plant. Too early seeding encourages foot rots (Robertson *et al.,* 1942a) and occasionally an excessive fall growth which exhausts the moisture and may be undesirable for other reasons. Seeding earlier than the optimum date is purposely practiced by many farmers in areas subject to wind erosion in the southern Plains in order that the wheat may make enough fall growth to protect the soil or to afford fall and winter pasture for livestock. Fall moisture is often a determining factor. Seeding early in dry soil is usually undesirable, since a light rain may germinate the grain but not provide enough stored moisture to maintain the plants. A common practice when the soil is very dry is to delay seeding as late as possible and then seed, with the hope that there will be sufficient precipitation to germinate the grain before spring.

Extensive tests of the time of seeding spring wheat show a marked decline in yields if it is seeded later than certain specified dates which, of course, vary greatly with latitude. In the extreme northern United States seeding may be as late as May 1 (Bell, 1937) without material reduction in yield, but seeding after the middle of May results in serious reduction. With modern equipment and barring weather extremes, the period for seeding after the ground thaws in the spring is long enough to avoid seriously late seeding.

h. Methods of Seeding Wheat. Practically no wheat is sown broadcast in the United States now, although it was a fairly common practice at the turn of the century for seeding spring wheat on corn ground. The main choice in methods of seeding for winter wheat at the present time is between the regular and furrow drills, the latter being widely used in much of the western part of the Plains area. In that section, surface moisture may be lacking at wheat seeding time, and the furrow drill may be able to place seed in moist soil when the regular drill does not. Increases in yield (Salmon, 1924; May and McKee, 1925; Quayle and Nelson, 1927; Brandon and Mathews, 1944) have resulted from its use at some locations, whereas at others yields have been about equal. A

relatively new development in drills are those that can plant through a heavy surface residue cover without clogging.

There have been many trials of seeding wheat in wide-spaced rows and cultivating in order to reduce the plant population and control weeds. In general, yield increases have been small or lacking, and not sufficient to offset the cost of cultivation. In a few cases in which weed growth, especially of winter annuals, has been excessive this practice may be practical for winter wheat.

i. Crop Rotation in the Great Plains. The expansion of the acreage of cultivated crops, particularly corn, into the Northern States has materially influenced cultural practices for wheat. Corn ground in the Northern States provides a seedbed that is intermediate in productiveness between small-grain land and fallow (Bell, 1937; Osenbrug and Mathews, 1951). On farms where wheat is grown as a cash crop, it is usually grown in the favored sequence, viz, after corn or other cultivated crops. The expansion of the sorghum acreage into the Northern States has had a similar effect (Osenbrug and Mathews, 1951), as yields of spring wheat on sorghum land have closely approached those after corn. Both corn and sorghum provide a clean-up crop that reduces the weed problem brought about through continuous production of small grains.

In the eastern portion of all the Plains states, adapted legumes and grasses are available and are used in rotations. Mixed farming is generally practiced, and production of feeds is of more importance than that of wheat, but wheat where grown is usually seeded in a favored place in the rotation.

The development of grain sorghums that can be handled with a combine has increased sorghum production in certain areas in the southern Plains that were formerly devoted almost entirely to wheat. This has forced the use of some fallow in the rotation, since yields after sorghums are materially below those of winter wheat after wheat in this area. The recommended practice of introducing a year of fallow between sorghum and wheat prevents this reduction in yield and results in a slightly greater portion of the wheat being grown on fallowed land.

In much of the Plains there is no grass or legume that is particularly well adapted for use in rotations, and their inclusion usually results in a reduction of income. Farming operations are directed toward moisture conservation rather than toward maintenance of fertility. The reductions in organic matter and nitrogen that have taken and are taking place (Myers *et al.*, 1943; Puhr, 1945; Volkerding and Stoa, 1947; and Zook, 1936), however, make it evident that one important future problem in the areas is to devise cropping systems that will check or reduce fertility loss without reducing the farm income materially.

j. Fertilizers in the Great Plains. The use of fertilizers for wheat production in the Great Plains is a relatively new and expanding development. In terms of state averages, the quantities used are still exceedingly small. In 1950 only one of the ten states showed an average use of more than 1 pound of nitrogen per acre, and only two showed a use of more than 1 pound P_2O_5 per acre. Only one of the ten states showed enough use of K_2O to be recorded, and the rate in that case was only 0.4 pound per acre.

In general there are three types of fertilizer response in the Plains. There is a belt, principally along the eastern edge, where yield increases from nitrogen or phosphorus or both are fairly common and regular. Further west, responses are not so regular, and the increases obtained in a small percentage of the years may or may not be high enough to make the practice profitable on the average. In the still drier portion of the Plains, yield increases may be obtained in a very few years, but average increases are unprofitable. Fertilizer requirement is determined both by soil fertility and moisture. The more nearly adequate the moisture is, the greater is the possibility that some factor other than moisture such as fertilizer will improve yields.

The Great Plains states have recently become intensely fertilizer conscious. Although some experimental work has been done for many years (Hutton, 1938), it is only recently that exploratory studies on a statewide basis have been made to determine the yearly and average responses that may be expected under the many different soil and climatic conditions.

5. *United States' Consumption of Fertilizer on Wheat*

The use of fertilizers in wheat production in the United States as a whole is too broad a subject to more than touch upon here. Perhaps some indication of its use on wheat may be gained by considering its use in general. A partial picture is presented in Fig. 13, which gives fertilizer consumption in the continental United States for the last forty years. Only a small part of that used is applied directly to wheat, but usually some residue of that applied to other crops may remain for wheat. It was estimated that 8.4 per cent of all fertilizer consumed in 1947 was applied directly to the wheat crop, which ranked fourth in order of fertilizer use following corn, all vegetables, and cotton. Over 90 per cent of the fertilizer applied to wheat was used in states lying east of the Great Plains and accounting for only about 20 per cent of the total wheat acreage.

Figure 13 shows a tremendous increase in the use of fertilizer since 1940. It emphasizes how important a factor fertilizers have been in the

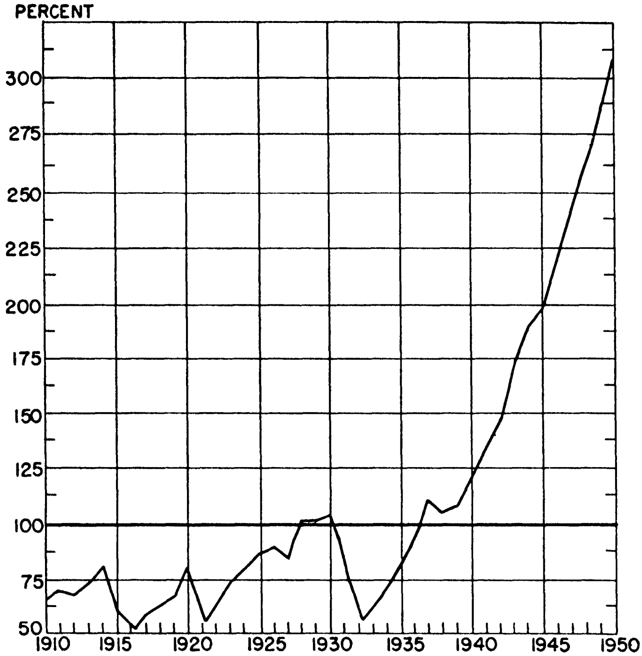

FIG. 13. Consumption of nitrogen, phosphoric acid, and potash in the continental United States from 1910 to 1950. (Index numbers; 1935 to 1938 = 100)

increased production of recent years. Although the use of fertilizer by wheat is still relatively small, it is probable that the wheat area as a whole has increased its fertilizer use by as great a percentage as that shown in the diagram.

6. *Mechanization of Wheat Culture*

Mechanization has been a highly important factor in the production of most crops in recent years. It began with wheat and has increased more rapidly with wheat than with any other crop. Johnson (1949) stated that "wheat production is almost completely mechanized." Many of the important improvements in production methods could not have been achieved without power machinery. Substitution of tractor-drawn for horse-drawn machinery has reduced the time required for farm operations, made it possible for the different operations to be done at the optimum time, enabled the farmer to do a better job, reduced labor costs, and taken much of the drudgery out of farming.

What mechanization means in reducing labor on the farm is illustrated by the data in Table V, reported by Cooper *et al.* (1947), showing the number of man-hours required to produce an acre of wheat at dif-

ferent periods in our history. The number of man-hours required per acre has been reduced by nine-tenths since about 1800 and by more than two-thirds since 1900. It has been further reduced by more than one-third since 1940. This means much in the way of improved practices. When horse-drawn implements were used and considerable hand labor was necessary, the farmer, regardless of intentions, was strictly limited by the physical impossibility of getting all of the work done at the proper time and in a satisfactory manner. The farmer who said he didn't want to learn anything more about farming "because I already know how to farm a lot better than I do" was making a simple statement of fact. Mechanization has changed that. Most farmers now can and do farm nearly as well as they know how.

TABLE V

Estimated Man-Hours Required to Produce an Acre of Wheat *

	About 1800	About 1840	About 1880	About 1900	About 1920	About 1940	About 1950
Man-hours per acre before harvest	16	12	8	7	5.5	3.7	3.0
Harvest	40	23	12	8	6.5	3.8	1.9
Total	56	35	20	15	12.0	7.5	4.9

* The writers are also indebted to Cooper *et al.* (1947) for data for 1950.

Mechanization did not arrive suddenly but has been more than fifty years in reaching its present state, with no sign that the limit of efficient use of mechanical power has been reached. At the beginning of the century the only mechanical power available was the steam engine, and this was used chiefly for pulling huge combines, or gangplows, or for belt work. Most of the combines were in California. They were adapted to large-scale heavy operations only. Gas engines came into commercial production early in the century, but the early models were cumbersome and were used only for heavy tillage, harvesting, and belt work. Track-laying tractors, now generally referred to as crawler tractors, came into production only a few years later. All of the early gas tractors were heavy, unwieldy, and expensive to operate. In spite of this they increased gradually through World War I and underwent gradual changes designed to reduce their weight and make them more generally useful.

Starters and lights for tractors were developed about 1920 and were another significant advance. The starter eliminated the dangers and labor associated with hand-cranking, and the lights made it possible to operate for long hours when necessary.

The development of the combine is one of the sagas of mechanized farming. Huge combines, pulled or self-propelled by a steam engine or sometimes pulled by as many as forty horses, were harvesting two-thirds of the wheat crop in California at the turn of the century (Fig. 10). Combines were commonly used in the Columbia and Snake River Basins while they were still a rarity in the Great Plains, but they were mostly horse-drawn (Fig. 9). Tractor operation did not become general in any area until in the twenties.

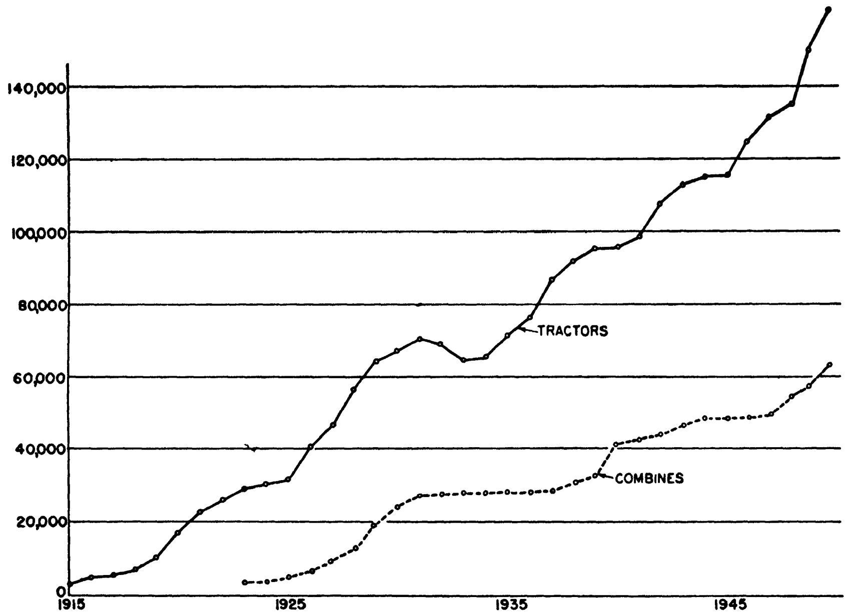

FIG. 14. Number of tractors and combines in Kansas from 1915 to 1950 (data from Kansas State Board of Agriculture).

Combines did not appear in the Great Plains in any numbers until after the end of World War I. They began to be used in slowly increasing numbers in the twenties but were generally large-sized machines use of which was confined principally to the semiarid region where large acreages were the rule. In the early thirties they were generally made lighter and more mobile, with smaller sizes predominating. In 1938 the self-propelled combines began to appear and have been gradually replacing other types on most wheat farms.

The number of tractors and combines in use in Kansas, a typical wheat state, is shown in Fig. 14. Combine numbers have been on the increase ever since smaller and more mobile types began to be available.

A development in 1935 that placed the combine on the smaller farms

was a practical one-man combine which "upset the old pattern and changed the very course of agriculture itself. . . . Since that time, the combine method of harvesting has become national rather than regional, the more expensive and laborious binding-shocking-thrashing method has been on its way out, and two great contributions to harvesting progress —the binder and the thresher—have largely fallen by the wayside" (Gittins, 1950).

The extent to which this has changed harvesting practices is shown in Table VI (Brodell *et al.,* 1952). In 1938 the per cent of wheat combined outside of the main producing areas was small indeed, although combines had been used in most of the Eastern States since about 1927. By 1950 by far the greater portion was being combined.

TABLE VI

Combined Harvesting of the Wheat Crop of the United States, 1938 and 1950

Region	Combined as standing grain or from windrow 1938	1950
	Per cent	Per cent
United States	49	94
Northeast	8	78
Corn belt	29	92
Lake States	8	81
Great Plains	55	95
Appalachian	6	67
Southeast	10	92
Delta	12	67
Oklahoma–Texas	75	99
Mountain	50	97
Pacific	84	99

The saga of the combine would not be complete without reference to the fleets of machines that do custom combining. Many of these start operating in Texas and move northward with the wheat harvest. They have greatly reduced the time required to harvest the wheat crop. In western Kansas, in a year unhampered by rains, the custom and locally owned machines have sometimes harvested the entire wheat crop of a county in little more than a week. The dependence on custom-operated machines is so great that many farmers do not own combines at all, and some that do, hire custom machines in addition to their own to speed the harvest.

The development of machinery for the tillage of wheat has been just as important if not as spectacular as that of the combine. Only a few of these can be mentioned. The rod weeder for cultivation of fallow land

appeared about 1910 and was supplanted about 1920 by the rotary rod weeder, which eliminated much of the trouble from clogging associated with the straight rod. The oneway or vertical-disk plow, first sold in large numbers about 1927, met with spectacular acceptance by farmers, particularly in the winter wheat area. It covered ground much more quickly than the plow, was effective in destroying weeds and volunteer wheat, and could be used for subsequent operations as well as for the initial one. It could also operate well on land so dry that plowing was about impossible. The oneway is the Dr. Jekyll and Mr. Hyde of tillage implements in that it can be operated so that it either protects the soil or exposes it to wind erosion. By adjusting the angle at which it is drawn and the speed of travel, it can do work ranging from almost complete covering of crop residues to leaving most of them on the surface.

Other important developments are the tractor tool bar, which made it possible for a farmer to operate a variety of tools without purchasing a separate complete outfit for each operation, tractor-mounted tools, and a wide variety of sweeps, blade and chisel implements that have found a place in wheat tillage operations.

It has been stated that without mechanization of wheat farming wheat rationing would have been necessary in World War II, instead of there being the abundant supplies available to feed us and our allies. The conditions that made such mechanization possible are discussed by Johnson (1949).

IV. The Role of Improved Varieties

No single fact so simply epitomizes the improvement in varieties during the last fifty years as does the complete disappearance of most of those known previous to 1900. Of the latter only one, TURKEY, now occupies more than one million acres. This variety in 1949 was grown on a little over three million acres or less than 4 per cent of the total national wheat acreage. Second in importance was FULTZ, with approximately 377,000 acres or less than 0.5 per cent of the total. Nationwide varietal surveys in 1919 and each five years thereafter (Clark *et al.*, 1922, 1929; Clark and Quisenberry, 1933, 1937, 1942, 1948; and Clark and Bayles, 1951) have provided a fairly accurate picture of the relative importance and distribution of individual varieties since 1900. Stoa (1945) has given an interesting account of the changes that have taken place in North Dakota, and Salmon and Bayles (1952) have recently presented charts showing important changes in the United States as a whole since 1919.

The improvement in varieties can be discussed most conveniently by wheat-growing regions. For this purpose the following districts or

regions may be recognized: (1) the hard red spring wheat region, (2) the durum wheat region, which geographically is in the hard red spring wheat region, (3) hard red winter wheat region, (4) eastern United States, and (5) western United States. Figure 15 shows the distribution of wheat in the United States, with each of these districts indicated.

The changes in varieties will be discussed separately for each region, and following this an attempt will be made to evaluate these changes in terms of increased yields, better quality, and reduction of wheat-growing hazards. An accurate evaluation is, of course, a difficult or even an impossible task. Occasionally, however, someone longs for the "good

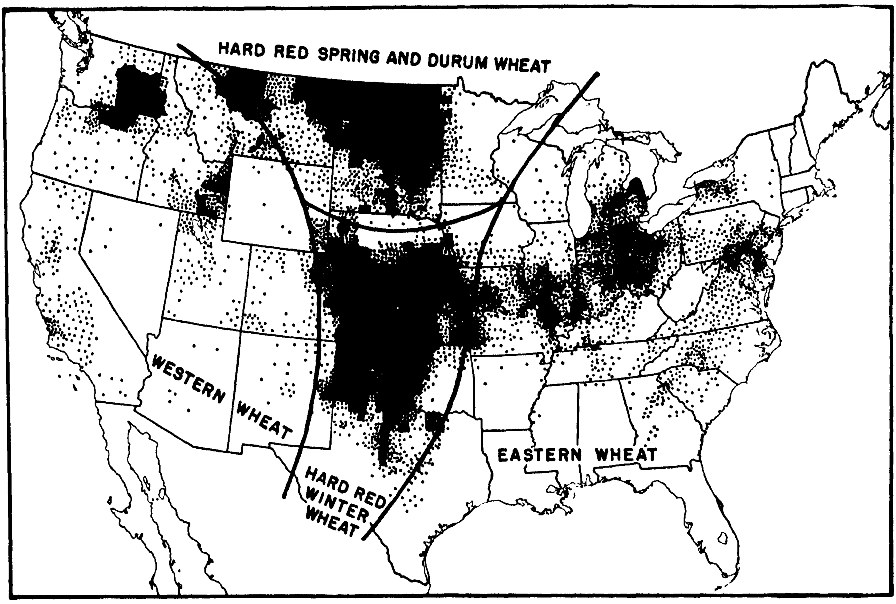

FIG. 15. Distribution of wheat seeded in the United States in 1919 and principal wheat-growing areas. Each dot represents 5,000 acres.

old varieties" and discounts the claims made for the new ones, just as there may be others who tend to overemphasize them. For this reason even rough estimates of improvements may be worth-while. Since lack of space precludes a full discussion of each region, the discussion for the first region to be considered will be somewhat more complete than that for the others.

1. Improved Varieties of Hard Red Spring Wheat

The wheat industry in the hard red spring wheat region developed with the varieties RED FIFE and BLUESTEM. RED FIFE found its way into

the North Central States soon after the middle of the nineteenth century and BLUESTEM appeared somewhat later. PRESTON under various names appeared near the close of the century and was generally grown in some localities. According to Stoa (1945), RED FIFE and related strains of FIFE dominated the picture before 1900. By 1914 (Yearbook, U.S. Department of Agriculture, 1920, p. 559) slightly more than half the crop of hard red spring consisted of BLUESTEM. On the basis of fairly extensive experimental trials in Minnesota, Montana, and the Dakotas, previous to 1900, those considered here, HAYNES BLUESTEM, RED FIFE, POWER, and PRESTON, are believed to be representative of, or at least as good as, any that were grown by farmers at that time.

The first important change in varieties after 1900 resulted from the introduction of the famous MARQUIS wheat from Canada in 1912 and 1913. MARQUIS was so immediately and generally popular that it was grown on more than 70 per cent of the hard red spring wheat acreage by 1919 and on nearly 90 per cent by 1929. It headed and ripened at least two to three days earlier than HAYNES BLUESTEM, and one or two days earlier than POWER and RED FIFE. By virtue of this fact it escaped some of the damage from stem and leaf rust in Minnesota and the eastern Dakotas, and from drought in the western part of the area. Having slightly shorter straw it lodged less. It was widely acclaimed by millers and processors and is still regarded by many as the ideal variety from the point of view of quality.

CERES, produced by the North Dakota Station, was distributed to farmers in 1926. Its particular virtue was slightly earlier maturity (about one day earlier than MARQUIS) and resistance to the then prevailing races of stem rust. It has also been widely regarded as being more drought-resistant than other varieties. To what extent this belief is due to its earlier maturity and hence to its tendency to escape the effect of drought is not precisely known. It is perhaps significant, however, that CERES survived definitely better than the others in laboratory tests at the North Dakota Station (Helgeson and Blanchard, 1940) in which young plants of CERES and other varieties were subjected to high temperature for a few hours. Also Bayles *et al.* (1937), Hubbard (1938), and Bartel (1947) found differences between CERES and other varieties with respect to certain physiological or morphological characteristics consistent with relative yields under drought conditions. It would appear, therefore, that CERES owes its high yield under drought conditions to something more than early maturity.

CERES was grown on nearly 35 per cent of the hard red spring wheat acreage by 1934. The acreage of MARQUIS had been declining in the meantime, and HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON had

practically disappeared. In about 1935 stem rust race 56, which attacks CERES as well as all the other varieties grown at that time, appeared in epidemic proportions. Both MARQUIS and CERES were badly damaged in the severe epidemic of that year, although yields of CERES were about double those of MARQUIS.

The famous THATCHER variety, produced in cooperative experiments with the Minnesota Station, was grown on 20,000 acres in 1935, having been released to farmers the previous year. THATCHER produced 20 bushels per acre or more in excess of CERES and MARQUIS on farms that year; and thereafter increased in acreage as rapidly as seed supplies would permit. It occupied more than 40 per cent of the spring wheat acreage by 1939, being at that time the most widely grown variety of hard red spring wheat. THATCHER was not only far superior to all others with respect to resistance to the prevailing races of stem rust but was also early (about two days earlier than CERES and three to five days earlier than MARQUIS), lodged but little, and proved to be of excellent quality. Because of its earliness it found a place not only in the eastern half of the area where stem rust is important but also in the western Dakotas and Montana, where it is still extensively grown.

But THATCHER is unusually susceptible to leaf rust and in 1938 and again in 1941 yielded substantially less in experimental trials than other new varieties, principally RIVAL and PILOT, which had been included in comparative trials at some of the North Dakota Stations as early as 1933. Both of these varieties were distributed to farmers in 1939 and soon replaced a considerable part of the acreage of THATCHER in Minnesota and the eastern half of the Dakotas.

MIDA was distributed by the North Dakota Station in 1944. Like RIVAL and PILOT, it was resistant to the prevailing races of leaf and stem rust, headed and ripened early in comparison with other varieties, did not easily lodge, and had excellent quality. It also increased rapidly and by 1949 was the leading variety of hard red spring wheat.

MIDA, RIVAL, and PILOT are bearded wheats. CADET, a beardless variety having stiff straw and excellent quality, was distributed to farmers in 1946. It heads and ripens three to four days later than THATCHER or about the same time as MARQUIS. It is grown only sparingly in western North Dakota and in some counties in the northern part of North Dakota.

Other varieties which should be mentioned include REGENT, RESCUE, and REDMAN, introduced from Canada; NEWTHATCH, produced in cooperative experiments at the Minnesota Station; and HENRY, at the Wisconsin Station. REGENT was grown on less than one-half million acres in 1949, mostly in North Dakota, REDMAN on about 135,000 acres, and NEWTHATCH on about 250,000 acres scattered throughout North Dakota and

western Minnesota. HENRY is grown mostly in Wisconsin. RESCUE is the only commercial variety grown in the United States that is resistant to wheat-stem sawfly. About one million acres are grown in the sawfly-infested area of northwest North Dakota and in northeast and north central Montana. Two new varieties, RUSHMORE and LEE, were released to farmers in 1949 and 1951, respectively.

Resistance to leaf rust has been an important objective in the breeding of all varieties since the distribution of THATCHER. As a consequence, all of the newer varieties are resistant to the races of leaf rust that were generally prevalent when they were released. Since then new races or

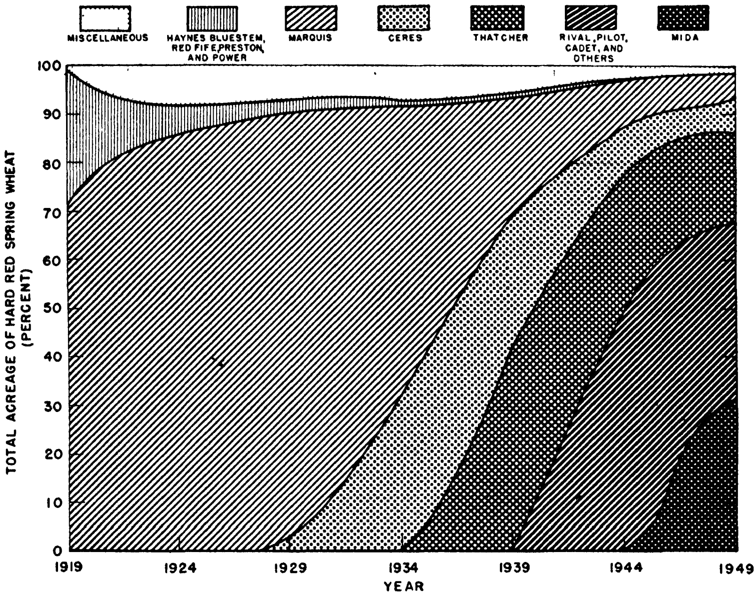

FIG. 16. Changes in acreages of important varieties of hard red spring wheat in the northern Great Plains (Minnesota, North Dakota, South Dakota, and Montana) from 1919 to 1949.

previously unimportant races have multiplied, with the result that none of them, with the possible exception of LEE, can be said to be generally resistant in the field.

The more important of the above changes are shown graphically in Fig. 16. The geographical distribution of each of the widely grown varieties in 1949 is shown graphically by Clark and Bayles (1951). It will be noted that MARQUIS and CERES now occupy only about 5 per cent each of the hard red spring wheat acreage. This is mostly in sections of Montana where rust is not a factor. THATCHER declined rapidly fol-

lowing severe leaf rust damage in 1938 and 1941, being largely replaced by RIVAL and PILOT and these in turn by MIDA soon after its release to farmers in 1944. A final evaluation of these varieties, as indeed of all others, in view of the prospective damage from race 15B of stem rust must await additional information.

a. Are the Improved Varieties Superior to the Old? What do these changes mean to growers and consumers of hard red spring wheat? To what extent have they resulted in larger yields and better quality, if any? Specifically, what would be the production of hard red spring wheat today if farmers had to depend on the varieties known to them before 1900? Any one familiar with the agricultural history of the area can scarcely doubt that they have been tremendously important. The evidence for this statement consists mostly of relative yields, quality characteristics, and resistance to disease, insects, and weather hazards of varieties grown in comparable experimental trials. These trials have been conducted for many years in each of the states that produce most of the spring wheat.

When MARQUIS was first included in these trials in about 1913, HAYNES BLUESTEM, POWER (POWERS FIFE), RED FIFE, and PRESTON were the principal varieties.

The results of experiments in which these varieties and others were compared have been reported by Atkinson and Donaldson (1916) and by Morgan and Bell (1926) for trials at Moccasin and Havre, Montana, respectively; by Towle (1930) for Sheridan, Wyoming; and by Hardies and Hume (1927) for Brookings and Highmore, South Dakota. Reports of early varietal trials in North Dakota have been published by Lanxon (1919), Walster (1920b), Thompson (1921), Ruzicka (1922), Kuenning (1925), and Moomaw (1925). Most of the North Dakota experiments have been summarized by Stoa (1921) and by Stoa *et al.* (1927). Results at Minnesota Stations have been reported by Wilson and Arny (1930). Most of the early experiments up to about 1919 have been summarized by Ball and Clark (1916) and by Clark *et al.* (1922).

CERES was recognized by research workers as a promising variety before it was distributed to farmers in 1926 and was generally included in experimental trials after 1925. As a result of the larger co-ordinated program initiated in 1928, THATCHER, RIVAL, PILOT, MIDA, and others were included in comparative trials throughout the region. Reports of many of these trials have been published by Klages (1931), Hayes *et al.* (1936), Stoa (1951), Hume (1940), Swenson (1942), Waldron *et al.* (1942), Harris *et al.* (1947), and Walster and Nystuen (1948). Waldron (1945) has presented an interesting tabulation of relative yields by five-year periods. Clark (1931–1950) has tabulated and presented in mimeo-

graphed form the principal field plot and nursery data for each station each year.

CERES was first included in comparative yield trials in 1923, THATCHER in 1929, RIVAL and PILOT in the mid-thirties, and MIDA in 1940 or 1941. Many varieties were discontinued as soon as their inferiority had been demonstrated. HAYNES BLUESTEM and RED FIFE have been included in recent yield trials only at Dickinson, North Dakota, POWER only at Fargo, and PRESTON not at all. MARQUIS was discontinued in many of the experiments in the early 1940's, and CERES has been discontinued from some of them. Although this procedure usually is justified under the circumstances, it is sometimes unfortunate when, as in the present case, there is need for long-time comparable records, either to evaluate varieties or to elucidate the principles on which varietal adaptation depends. Thus direct comparisons between MIDA and the old varieties HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON can be made at very few places and for a few years only.

It appears that the best that can be done in the present case is first to compare MARQUIS with the old varieties HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON; then CERES with MARQUIS; THATCHER with CERES; RIVAL, PILOT, and MIDA with THATCHER; and finally to make such direct comparisons as are possible between the newer varieties and the old. Both methods suffer from certain defects, but the former has the advantage of including most of the yield data.

(*1*) *Relative yields.* Table VII shows the comparative yields obtained by these various comparisons from nearly all unirrigated varietal field plot experiments conducted for five years or more in central and western Minnesota, North and South Dakota, northern Wyoming, and central and eastern Montana. They do not include nursery plot trials except for a few stations where in recent years replicated multiple-row nursery plots have been substituted for field plots. The newer varieties include only those which were grown on 250,000 acres or more in 1949. One variety, RESCUE, which was grown on more than 250,000 acres is not included for reasons stated later. The varieties are arranged from left to right roughly in the order in which they were released to farmers. MIDA is compared with THATCHER rather than with RIVAL and PILOT, since the number of stations and years in the two cases are almost identical. RIVAL and PILOT are considered together, since they are similar in plant type, dates of heading and ripening, resistance to rust, and yield.

The data are presented separately for the eastern half of the area, where leaf and stem rusts are dominant yield factors, and for the western half of the area, where drought and high temperatures are more important. The 100th meridian is the approximate dividing line, al-

though data from three stations, Highmore, Eureka, and Mandan, which lie slightly west of this meridian are included in the eastern section because rust-resistant varieties at these stations have generally outyielded susceptible varieties. It should not be assumed, however, that this is an accurate classification; rust has at times caused serious loss in the western Dakotas and even in Montana, and drought is not unknown even as far east as St. Paul, Minnesota.

It will be seen that in the eastern section MARQUIS produced higher average yields than any of the four varieties that preceded it and that in turn CERES has yielded more than MARQUIS; THATCHER more than CERES; and RIVAL, PILOT, and MIDA more than THATCHER. The same is true in the western section except that RIVAL, PILOT, and MIDA are not higher-yielding than THATCHER. Of these latter varieties only PILOT and MIDA are grown extensively west of the 100th meridian, and they, only in western North Dakota. The differences in yield in the original tables, which are summarized in Table VII, were remarkably consistent in most cases. In the eastern section MARQUIS failed to average more than HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON in only one trial, viz, St. Paul, Minnesota, for 1913–1915 and for 1918–1927. In this case PRESTON outyielded MARQUIS by 0.4 bushel. On the average for all years at each station CERES outyielded MARQUIS, THATCHER outyielded CERES, MIDA outyielded THATCHER, and RIVAL or PILOT failed to outyield THATCHER at only two stations and then by less than a bushel in each case. Likewise at all stations in the western area MARQUIS on the average outyielded HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON; CERES outyielded MARQUIS; and THATCHER outyielded CERES. In the remainder of the trials in the western region, i.e., those in which RIVAL, PILOT, and MIDA are compared with THATCHER, the average yields were often but not always in favor of THATCHER. This is in line with the comparative acreages of these varieties and THATCHER west of the 100th meridian.

The question naturally arises as to whether a useful estimate of the over-all gains in yield may be had by adding the successive gains. Clearly such a procedure is not justified if there is a change in yield levels. Leaf and stem rust have occurred much more frequently since 1913 than before; hence, part of the differences in yield merely offsets the tendency for yield levels to decline. There is also evidence to indicate, as pointed out by Stoa (1951), that differences in yield between rust-resistant and rust-susceptible varieties tend to become less as new races of the rust organism appear. On the other hand, the earlier heading and ripening of the newer varieties has enabled them to escape some of the damage that would otherwise have occurred because of rust, drought, and high temperature. To the extent that increase in rust

TABLE VII

Comparative Yields of Important Varieties of Hard Red Spring Wheat in the Northern Great Plains *

Item and section	Number of station years	Average yields, bu./acre									
		RED FIFE	POWER	HAYNES BLUESTEM	PRESTON	MARQUIS	CERES	THATCHER	RIVAL	PILOT	MIDA
Eastern section	29			15.0		19.7					
	59		17.8			20.3					
	69				19.1	20.0					
	199					16.6	19.9				
	157						18.8	21.2			
	135							23.7	26.5		
	147							23.5		25.3	
	99							24.9			28.3
Difference compared with											
MARQUIS		,	—2.5	—4.7	—0.9		+3.3				
CERES								+2.4			
THATCHER									+2.8	+1.8	+3.4
Western section	67			13.5		16.3					
	60		19.1			20.6					
	45	15.1				16.5					
	22				14.3	16.0					
	119					18.7	20.7				
	86						20.5	21.2			
	35							21.9	20.7		
	68							22.6		22.2	
	36							27.2			26.8
Differences compared with											
MARQUIS		—1.4	—1.5	—2.8	—1.7		+2.0				
CERES								+0.7			
THATCHER									—1.2	—0.4	—0.4

* The original data from which this table was prepared have been published, as indicated in the text, or they were obtained in cooperation with the Agricultural Experiment Stations of Minnesota, South Dakota, North Dakota, Montana, and Wyoming.

damage and new races of rusts have been important, adding successive gains in yield would not be a valid procedure. Fortunately, this can be determined to some degree by comparing the newer varieties THATCHER, RIVAL, PILOT, and MIDA with certain of the old varieties at two stations, Fargo and Dickinson, North Dakota.

It is well known that yields in experimental trials are often higher than those in farmers' fields and that differences between varieties often increase as yields increase. To correct for this tendency, yield differences between varieties in the original tables for the varietal pairs shown

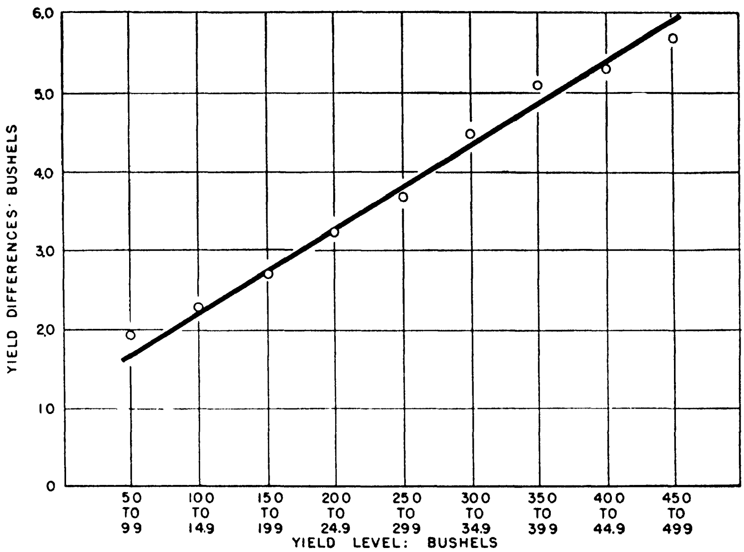

FIG. 17. Relation between differences in yield in varietal pairs and the yield level in experimental yield trials.

($r = 0.9818$. $y = 0.97 + .104X$. $N = 6675$)

in Table VII were tabulated and averaged for different yield levels. The same was done for each of the other three wheat regions, and since the results were substantially alike, they were combined and are shown here as a graph in Fig. 17. Observed differences for hard red spring wheat were then adjusted on the basis of this graph to a yield level of 14.5 bushels per seeded acre, which is approximately the average yield of all hard red spring wheat in Minnesota, North Dakota, South Dakota, and Montana for the period 1941–1950. It may be noted from Fig. 17 that the relation between yield levels and yield differences is linear and that yield differences decline almost precisely 1 bushel for each 10 bushels difference in yield level.

Table VIII shows the average gains for each successive new variety as compared with the one or more that preceded it before and after adjustment to yield levels and the estimated accumulated gains. The latter are derived by adding the successive gains. The estimated gain shown for MARQUIS in this table is the weighted average of those shown in Table VII.

TABLE VIII

Estimated Gain in Yield for Improved Varieties East and West of the 100th Meridian (Approximately) before and after Adjustment for Yield Levels

	East of 100th meridian			West of 100th meridian		
Item	No. of station years	Before	After	No. of station years	Before	After
		Adjustment, bu./acre			Adjustment, bu./acre	
Average gain for:						
MARQUIS over HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON	128*	2.2	1.5	98*	2.0	1.9
CERES over MARQUIS	199	3.3	2.8	119	2.0	1.5
THATCHER over CERES	153	2.4	1.8	86	0.7	0.1
RIVAL over THATCHER	135	2.8	1.7	35	1.2	0.0
PILOT over THATCHER	147	1.8	0.8	68	—0.4	0.0
MIDA over THATCHER	99	3.4	2.1	36	—0.4	0.0
Total accumulated gain for:						
CERES over HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON			4.3			3.4
RIVAL over HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON			7.8			
PILOT over HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON			6.9			3.5
MIDA over HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON			8.2			3.5
THATCHER over HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON			6.1			3.5

* The number of station years for the comparison of MARQUIS with the older varieties is not the sum of those given in table VII since in many cases more than one was compared with MARQUIS in the same experiments.

The gains estimated by direct comparison and by adding successive gains at Fargo and Dickinson are compared in Table IX. In some cases the direct comparison indicates a lesser gain and in others a greater gain than is obtained by adding successive gains. On the whole, the agreement seems to be as good as could be expected considering the relatively short testing periods in some cases and the sharp fluctuations in yield differences from year to year due in the main to whether rust was or was not a factor.

In this connection it should be noted that differences between rust-resistant and rust-susceptible varieties have been in general substantially less during the last ten years than in previous years, owing presumably to less damage by rust. Since the estimates of increases secured by accumulating gains as in Table VII are based on a much larger number of trials representing more years and more stations, it would appear reasonable to consider them more reliable for estimating the increases for the area as a whole than are those for Fargo and Dickinson alone (Table IX). They accordingly are used to estimate the increases in production due to the improved varieties, as shown in Table X.

TABLE IX

Estimates of Increased Yields at Fargo and Dickinson, North Dakota, by Accumulating Gains and by Direct Comparison before and after Adjustment to Average Yield Levels

Item and location	Number of station years	Estimated gains Before Adjustment bu./acre	Estimated gains After Adjustment bu./acre
Fargo, N. Dak.			
Average gains			
MARQUIS over POWER, 1913–1914, 1916–1950	37	+2.6	1.4
CERES over MARQUIS, 1923–1950	28	+3.5	2.6
THATCHER over CERES, 1930–1950	21	+1.4	0.3
MIDA over THATCHER, 1940–1950	11	+1.8	0.5
MIDA over POWER			
By accumulating gains		9.3	4.8
By direct comparison, 1940–1950	11	6.4	5.1
THATCHER over POWER			
By accumulating gains		7.5	4.3
By direct comparison, 1930–1950	20	6.2	5.7
Dickinson, N. Dak.			
Average gains			
MARQUIS over HAYNES BLUESTEM and RED FIFE, 1913–1950	38	+1.9	1.9
CERES over MARQUIS, 1923–1950	28	+2.2	2.1
THATCHER over CERES, 1930–1950	21	+1.3	1.3
MIDA over THATCHER, 1940–1950	11	+1.5	0.9
MIDA over HAYNES BLUESTEM and RED FIFE			
By accumulating gains		6.9	6.2
By direct comparison, 1940–1950	11	6.2	5.6
THATCHER over HAYNES BLUESTEM and RED FIFE			
By accumulating gains		5.4	5.7
By direct comparison, 1930–1950	21	4.2	4.2

TABLE X

Estimated Annual Increases in Production for Improved Varieties of Spring Wheat as Compared with HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON in 1949

	Estimated acreage		Estimated increases	
Variety	East of the 100th meridian	West of the 100th meridian	Yield per acre, bu.	Production, bu.
MIDA	3,554,000		8.2	29,143,000
		2,000,000	3.5	7,000,000
RIVAL	2,931,000		7.8	22,862,000
PILOT		571,000	3.5	1,999,000
THATCHER		3,371,000	3.5	11,799,000
CERES		1,185,000	3.4	4,029,000
MARQUIS		882,000	1.9	1,676,000
NEWTHATCH	92,000		6.1	561,000
		190,000	3.5	665,000
REGENT	221,000		6.1	1,348,000
		220,000	3.5	770,000
CADET	200,000		6.1	1,220,000
		426,000	3.5	1,491,000
Total:				84,563,000

(2) Increase in production. Table X is based on the estimated acreage of each variety seeded on 250,000 acres or more in Minnesota, North Dakota, South Dakota, and Montana in 1949, as reported by Clark and Bayles (1951) and approximately as distributed in the eastern and western sections. Multiplying these by the estimated increase in yield which may properly be attributed to each variety from Table VIII gives the estimated increase in production for 1949 shown in the last column of Table X. In arriving at these estimates the gain in yield for REGENT, MIDA, CADET, and NEWTHATCH are assumed to be the same as for THATCHER. These latter assumptions may not be strictly accurate, but the acreage affected is so small that the effect on the over-all estimate may be ignored. The variety RESCUE is not included. It is known to yield less than other varieties when wheat-stem sawfly is not a factor, but, without doubt, it produces higher yields in the area where it is grown because of less sawfly damage. No data are available to show what this gain is.

These data indicate a gain of 84,563,000 bushels on an area of 16,840,000 acres. The average acreage of hard red spring wheat in the four states for 1941–1950 is 14,177,000. Adjusting the indicated gain to this acreage brings it down to 71,191,000 bushels. But this does not take

into account the improvement in test weight per bushel and the greater yield of flour from the stem rust-resistant varieties. As will be seen later, the differences between test weights of the improved varieties compared with HAYNES BLUESTEM, RED FIFE, POWER, and PRESTON varied from 0.1 to 1.9 pounds per bushel for the western area and from 4.3 to 6.8 pounds for the eastern, or roughly an average of 1 pound per bushel for the western section and 5 pounds per bushel for the eastern. Assuming a decrease in flour yield of three-fourths of 1 per cent for each pound reduction in test weight, as was reported by Thomas (1917) and by Coleman (1935), applying this to the average production per year of 204,000,000 bushels for the 1941–1950 period, and assuming an equal division between the two areas indicates a gain in production of flour of about 275,000,000 pounds, equivalent to about 6,500,000 bushels of wheat. This, added to the above, gives a total indicated gain of about 77,691,000 bushels of wheat.

The durum wheats must be included to complete the picture for the spring wheat region as a whole. On the basis of tests at Langdon and Fargo, North Dakota, which probably best represent the durum wheat area, the best durum varieties may be expected to yield about 1 bushel per acre more than MIDA. This gives an estimated gain of 9.2 bushels per acre which, applied to the 2,600,000 acres of durum, suggests an additional increase in production of 23,920,000 bushels, thereby bringing the total to 101,611,000 bushels per year.

This represents an average gain of 6.1 bushels per acre. Waldron (1943) compared the total production of wheat in North Dakota in 1941, 1942, and 1943 with that in 1914, 1915, and 1916, having found that the temperature and moisture supplies for the two periods were substantially alike. The average gain calculated from his data was about 5.0 bushels per acre. Most of the North Dakota acreage consisted of stem rust-resistant varieties in the later period, whereas MARQUIS and other susceptible varieties only were grown during the 1914–1916 period. Craigie (1944) also estimated the increase in yield due to resistant varieties as 5.2 bushels per acre in Manitoba and 3.0 bushels in Saskatchewan, Canada.

A high degree of accuracy, of course, cannot be claimed for the estimates presented here. It depends on many assumptions that cannot be verified however reasonable they may appear to be. It assumes, among other things, damage from leaf and stem rust comparable to that suffered during the periods of these tests. It assumes also that the reduction in rust damage during the past decade is due solely to resistant varieties. Eradication of barberries has, no doubt, also been a factor. If the old susceptible varieties had been grown exclusively, the build-up

of inoculum would not have been impeded to the same degree, and damage would undoubtedly have been much greater than has been the case. Peturson (1949) in Canada has shown that the substitution of stem rust-resistant for susceptible varieties reduced the number of stem rust spores in the air over western Canada.

A reduction in average yield of even 5 bushels per acre would mean a reduction of three to four times that amount on individual farms in bad stem rust years, which in turn would mean that some farmers would discontinue growing wheat and turn to other crops. Similar effects have been recorded in the past, as in Iowa, southern Minnesota, and southeastern South Dakota and with other crops and diseases elsewhere. It requires no stretch of the imagination to visualize a material reduction of the wheat acreage under such conditions.

On the other hand, there can be no assurance that this gain in production will be maintained in the future. It will not if race 15B and other new races of leaf rust that attack MIDA, RIVAL, and other new varieties continue to replace other races and if satisfactory new varieties of wheat resistant to them are not produced. If such should be the case, the only gains in production that could be expected are those due to the earlier maturing and better yields of the improved varieties because of their ability to escape the effects of rust, drought, and hot winds. On the basis of relative yields in years when neither leaf nor stem rust were yield factors, this might be expected to be 2 or 2.5 bushels per acre or perhaps 30,000,000 to 35,000,000 bushels per year, assuming the present acreage of wheat.

(3) Relative weights per bushel. Varieties with relatively high bushel weights or test weights are desired by farmers because test weight is an important grading factor and by millers because of its relation to flour yield. Relative weights per bushel of the more important varieties are compared in Table XI, the source of the data being the same as that for yields. The principal factors that determine relative test weights, other than inherent characteristics of the varieties themselves, are stem rust, drought, and high temperatures during the fruiting period. MARQUIS, it will be noted, is definitely superior to HAYNES BLUESTEM and slightly better than POWER in the eastern section. CERES, on the average, has weighed 2.8 pounds per bushel more than MARQUIS, an expression largely of its greater resistance to stem rust especially during the earlier years. THATCHER often weighs less per bushel than either CERES or MARQUIS when stem rust is not a factor, but in the eastern section this tendency has been overbalanced by the effect of stem rust. RIVAL and especially MIDA are outstandingly superior with respect to test weight. PILOT averages about the same as THATCHER.

TABLE XI

Comparative Weights per Bushel of Important Varieties of Hard Red Spring Wheat *

Section and item	Number of station years	Average weight per bushel, pounds									
		RED FIFE	POWER	HAYNES BLUESTEM	PRESTON	MARQUIS	CERES	THATCHER	RIVAL	PILOT	MIDA
Eastern section	34		55.1			55.8					
	13			49.7		52.6					
	129					53.4	56.2				
	134						56.1	56.3			
	131							56.6	58.0		
	109							56.4		56.6	
	97							56.8			59.3
Difference compared with											
MARQUIS			—0.7	—2.9			+2.8				
CERES								+0.2			
THATCHER									+1.4	+0.2	+2.5
Western section	42	56.7				57.5					
	99		56.2			56.4					
	96			53.1		56.2					
	52				57.0	56.0					
	86					57.5	58.4				
	75						58.3	56.5			
	22							57.6	58.1		
	46							55.9		55.7	
	36							57.7			59.5
Difference compared with											
MARQUIS		—0.8	—0.2	—3.1	+1.0		+0.9				
CERES								—1.8			
THATCHER									+0.5	—0.2	+1.8

* See footnote to Table VII.

In the western section, MARQUIS again is characterized by a definitely higher weight per bushel than HAYNES BLUESTEM, slightly better than POWER and RED FIFE, but lower than PRESTON. CERES is higher than MARQUIS, but the difference is considerably less than in the eastern section. RIVAL and MIDA are higher than THATCHER, the differences again being less than in the eastern section.

Adding these gains as was done for yields provides the data in Table XII for the estimated improvement in weight per bushel over HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON.

Since the environmental factors (other than leaf rust) that affect weight per bushel are much the same as those that affect yields, the interpretation of these results is subject to much the same limitations as is that of the estimated gains in yield discussed above.

(4) Quality characteristics. Quality has received as much attention as any other characteristic in developing new varieties of wheat in recent years. The improved varieties are as good as the old with respect to all important characteristics and better with respect to many.

TABLE XII

Estimated Improvement in Weight per Bushel over HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON

Variety	Estimated gain in pounds per bushel over HAYNES BLUESTEM, POWER, RED FIFE, and PRESTON — Eastern Section	Western Section
MARQUIS	+1.3	+1.0
CERES	+4.1	+1.9
THATCHER	+4.3	+0.1
RIVAL	+5.7	+0.6
PILOT	+4.5	+0.3
MIDA	+6.8	+1.9

MARQUIS was enthusiastically accepted by the milling and baking industries almost immediately after its introduction, and experimental milling and baking trials have unanimously supported this verdict. Results of comparative trials in which various milling, baking, chemical, and physical characteristics of MARQUIS have been compared with those of HAYNES BLUESTEM, POWER, RED FIFE, PRESTON, and others grown in experimental plots at Havre, Montana, have been reported by Morgan and Bell (1926) and in North Dakota by Stoa *et al.* (1927). Most of these data and those from other experiments have been summarized by Clark *et al.* (1920) and by Shollenberger and Clark (1924).

Without exception the flour from MARQUIS produced a superior loaf of bread. This, plus the handling properties of the dough, which adapted it to large-scale bakery operations, was principally responsible for its popularity with millers and bakers. Because of its earliness MARQUIS was often damaged less by stem rust, heat, and drought, and for that reason sometimes had a higher weight per bushel (Table XI) and produced more flour.

MARQUIS has been compared with the newer varieties, and they in turn with each other in extensive milling and baking trials. In these trials MARQUIS was used as a standard of comparison until it was discontinued in many field trials, after which THATCHER was used for this purpose. Some of these results have been reported by Wilson and Arny (1930); Hayes *et al.* (1936); Ausemus *et al.* (1938); Stoa *et al.* (1941, 1942); Waldron *et al.* (1942); Harris *et al.* (1947); Harris and Sibbitt (1949); Finney and Barmore (1948); and Fifield *et al.* (1950). Fifield *et al.* (1936–1950) have reported the results of milling and baking experiments with hard red spring wheat each year from 1929 to 1950. Since these data are not generally available, the more important of them for the period 1937–1950 are summarized in Table XIII.

The results are in substantial agreement with those reported by others in indicating an equal or higher flour yield, protein content, and loaf volume for all of the improved varieties as compared with MARQUIS.

The protein content of the stem rust-resistant varieties is as high or higher than that for the susceptible varieties MARQUIS and CERES, and consequently they produced more protein per acre especially in the eastern sections. In such comparisons, the usual inverse relation between yield and protein content does not apply, since rust reduces the yield but does not greatly affect the percentage of protein in the grain. Whether nitrogen is left in the straw of susceptible varieties, used by the rust organism, or dissipated in other ways is not known with certainty. Snyder (1905) showed that in certain samples rusted straw contained nearly twice as much nitrogen as the rust-free straw.

In the eastern section the flour yield of MARQUIS is definitely less than that of CERES, and CERES in turn produces less flour than THATCHER, largely owing no doubt to the differences in test weight as a result of stem rust damage. MIDA and RIVAL definitely appear to produce more flour than any others, and PILOT about the same as MARQUIS and CERES.

For equal or near equal test weights, THATCHER usually produces more flour than either MARQUIS or CERES. Both RIVAL and MIDA appear to be definitely superior to all others with respect to flour yield as well as to test weight. Probably the data for flour yield in this table do not fully reflect the differences that would normally occur for the reason that

TABLE XIII

Protein Content of the Grain, Yield of Flour, and Loaf Volume of Bread of Important Varieties of Hard Red Spring Wheat *

Section and item	Number of station years	MARQUIS	CERES	THATCHER	RIVAL	PILOT	MIDA
	Protein content, %						
Eastern section	13	13.4	13.9				
	29		14.2	14.7			
	105			14.3	14.2		
	100			14.4		14.2	
	91			14.1			14.2
Difference compared with							
MARQUIS			+0.5				
CERES				+0.5			
THATCHER					—0.1	—0.2	+0.1
Western section	44	15.1	15.3				
	53		15.3	15.6			
	35			15.4	15.2		
	58			15.5		15.2	
	43			15.4			15.0
Difference compared with							
MARQUIS			+0.2				
CERES				+0.3			
THATCHER					—0.2	—0.3	—0.4
	Flour yield, %						
Eastern section	13	66.4	69.5				
	29		71.4	72.3			
	105			72.5	74.4		
	100			72.4		71.5	
	91			72.8			74.5
Difference compared with							
MARQUIS			+3.1				
CERES				+0.9			
THATCHER					+1.9	—0.9	+1.7
Western section	44	70.6	71.6				
	53		71.5	72.0			
	35			71.7	73.1		
	58			71.9		70.9	
	43			72.6			74.5
Difference compared with							
MARQUIS			+1.0				
CERES				+0.5			
THATCHER					+1.4	—1.0	+1.9

TABLE XIII—*Continued*

Section and item	Number of station years	MARQUIS	CERES	THATCHER	RIVAL	PILOT	MIDA
	Loaf volume, cc.						
Eastern section	13	766	786				
	29		824	839			
	105			844	827		
	100			844		841	
	91			855			808
Difference compared with							
MARQUIS			+20				
CERES				+15			
THATCHER					—17	—3	—47
Western section	44	859	853				
	53		837	874			
	35			842	832		
	58			872		882	
	43			869			838
Difference compared with							
MARQUIS			—6				
CERES				+37			
THATCHER					—10	+10	—31

* The milling and baking experiments from which these data were derived other than those by the State Agricultural Experiment Stations and referred to in the text were conducted in cooperation with the Grain Branch, Production and Marketing Administration, United States Department of Agriculture.

in choosing samples for milling and baking trials, low bushel weight lots of grain were often rejected. This limitation, however, does not apply to the weight per bushel data of Tables XI and XII.

THATCHER and PILOT are definitely superior to all others with respect to loaf volume. Some bakers have objected to THATCHER, however, because of its "bucky" dough. It is generally recognized as a superior variety for blending with weaker wheats. Loaf volumes and dough handling properties of MIDA are very similar to those of MARQUIS. RIVAL and MIDA appear to be at least the equal of MARQUIS in average loaf volume.

Protein content, flour yield, and loaf volumes are, of course, not the only factors considered in evaluating milling and baking qualities. In the absence of other defects, however, they are the determining factors. Other factors are not considered in detail here since none of these vari-

eties appear to be inferior to MARQUIS with respect to any other milling and baking characteristic.

(5) Other characteristics. All of the improved varieties ripen earlier than the old varieties; this sometimes helps in completing field operations. With the exception of PILOT, they lodge less. MARQUIS, CERES, and THATCHER, like all of the old varieties, are moderately susceptible to the races of bunt that generally prevail in the northern Great Plains. CADET appears to be in about the same class as THATCHER. On the other hand, PILOT, RIVAL, and MIDA are definitely resistant. MIDA is susceptible to loose smut, as also is LEE. RIVAL and MIDA tend to shatter somewhat more than the old varieties and likewise more than the other new ones. MIDA also is somewhat more susceptible than others to late spring freezes. Sprague (1946) has reported that none of the spring wheats is really resistant to the complex of foot rots of the northern Great Plains. Some are more tolerant than others, however, the best in this respect being PILOT and RIVAL. As indicated above, all are susceptible to stem rust race 15B and, with the exception of LEE, to the races of leaf rust generally prevalent in the area. They are not by any means perfect wheats, but in the most important characteristics they are equal and in most cases far superior to the varieties they replaced.

2. Improved Varieties of Durum Wheat

The principal achievements in breeding durum wheats are improvement in quality, protection against new races of stem rust, and some improvement in yield. Before Carleton went to Russia in 1898, the only variety of durum wheat grown commercially in the United States was the ARNAUTKA variety, often known as GOOSE wheat in North Dakota and as NICARAGUA in Texas. Carleton brought back a considerable number of varieties from Russia, including KUBANKA, ARNAUTKA, GHARNOVKA, and PERODKA. At about the same time, PELISS and KAHLA were brought in from North Africa and GOLDEN BALL from South Africa. The Russian varieties soon proved superior in both yield and quality. The KUBANKA and ARNAUTKA varieties were soon recognized as probably the best on the basis of yield and quality tests, and seed of these was widely distributed by the North and South Dakota Stations and the United States Department of Agriculture soon after 1900. They became the leading varieties soon after the turn of the century.

Bolley of the North Dakota Station introduced two varieties, later named PENTAD and MONAD, from Russia in 1903 and distributed them in North Dakota in 1911. Both were highly resistant to stem rust but of poor quality. PENTAD, also known as RED DURUM, because the grain is red rather than amber, has been grown quite extensively at various times,

especially for late seeding, and is still grown to a limited extent for feed. It was grown on as much as one million acres in 1929. In addition to purifying KUBANKA and ARNAUTKA for distribution to farmers, several pure-line selections were made at various times during the first quarter of the century. The principal ones were ACME and NODAK, both selected from KUBANKA; the first at the South Dakota Branch Station at Highmore and the latter at the North Dakota Branch Station at Dickinson, and in cooperation with the United States Department of Agriculture. ACME was grown commercially in 1916, and NODAK was distributed to farmers in 1923. Both were more resistant to stem rust than KUBANKA but, in general, were deficient in quality and were never grown extensively. The first significant improvement beyond the purification and increase of the better varieties was effected at the Minnesota Station in the variety MINDUM, selected in 1896 from the common wheat called HEDGEROW but not distributed to farmers until about 1917 (Hayes and Garber, 1919). Its outstanding characteristics are superior quality and resistance to the prevailing races of leaf rust and to some races of stem rust previous to 1950. It has been an important variety for more than forty years.

STEWART and CARLETON were produced by backcrossing a VERNAL EMMER X MINDUM cross to MINDUM in a cooperative breeding program started by the North Dakota Station and the United States Department of Agriculture at Langdon, North Dakota, in 1929. These varieties were released to farmers in 1943. Their principal advantages are resistance to the prevailing races of stem rust, including the so-called durum races 17 and 21, but not to race 15B. Their quality is fully equal to that of MINDUM. CARLETON has stiff straw and for that reason is popular for growing on fallow or where severe lodging is expected but elsewhere has given lower yields than MINDUM (Stoa *et al.*, 1946). STEWART has consistently outyielded MINDUM and has become the leading variety of durum wheat. Two other varieties, VERNUM and NUGGET, released to farmers in 1947 and 1951, respectively, are considered desirable for the southern half of the durum territory because of their early maturity. In general, they have yielded less than the more commonly grown varieties. The history of durum varieties in North Dakota has been discussed by Stoa (1945).

The changes in the more important varieties in the United States that have taken place since 1919 are shown in Fig. 18. In this figure KUBANKA and ARNAUTKA are considered together, since in the varietal surveys farmers often did not distinguish between them but simply reported them as "durum wheat." The changes in durum varieties until recent years, it will be noted, have been fewer and less striking than for

the common spring wheat, owing, no doubt, to the fact that much less effort has been devoted to durum wheat breeding.

a. Relative Yields. The new durum varieties have been so favorably received by processors and farmers generally that there can be little doubt as to their superior quality and yield. Yield data are not available to accurately evaluate the gains. KUBANKA is the only old variety that has been continued in experimental trials. The results of early experiments in which KUBANKA was compared with other varieties have been reported by Ball and Clark (1918). KUBANKA has been compared

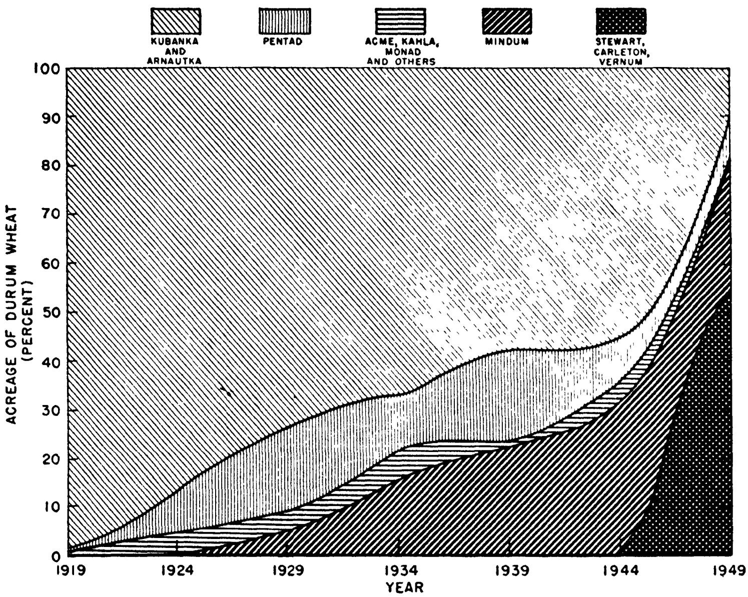

FIG. 18. Changes in the acreages of important varieties of durum wheat in North Dakota, South Dakota, and Minnesota from 1919 to 1949.

with the new improved varieties for a substantial number of years in the strictly durum wheat area at only two stations, Fargo and Langdon, North Dakota.

Comparative yield and other characteristics of the improved varieties as compared with KUBANKA at Fargo and Langdon and other stations in North Dakota have been reported by Stoa (1945), Stoa *et al.* (1941, 1942, 1946), Smith (1943), and by Clark (1931–1950). At Langdon the average yields for the twenty-five-year period (1927–1951) are 30.1 bushels for MINDUM and 29.0 for KUBANKA. Likewise at Fargo for a period totaling twenty-one years (1920–1926; 1930–1943) the average yield for MINDUM is 31.4 as compared with 28.5 for KUBANKA. This is

an average gain for MINDUM of 2 bushels per acre. For the nine-year period in which STEWART has been included it has outyielded MINDUM by about 2 bushels at Langdon but by slightly less at Fargo. Adjusting these differences to yield levels as was done for the common spring varieties suggests an average gain on farms of about 1 bushel per acre as compared with MINDUM, or a total gain of about 1,344,000 bushels per year. This is probably a conservative estimate, since during the period in which STEWART and CARLETON have been tested there has been no appreciable rust damage to the durum wheats at Fargo or Langdon except that due to race 15B in 1950. Since STEWART and CARLETON are known to be highly resistant to stem rust races 17 and 21 whereas MINDUM and KUBANKA are not, it seems probable that had these latter varieties been grown exclusively the damage from these races would have been much greater. Evidence that MINDUM and STEWART outyield KUBANKA are available from Crookston and Morris, Minnesota, on the fringe of the durum wheat area. The average fifteen-year differences in yield in favor of MINDUM are 3.0 and 2.8 bushels per acre, respectively. STEWART has yielded substantially the same as MINDUM at these stations, and CARLETON, about 2.5 bushels less than MINDUM.

3. *Improvement of Varieties for the Hard Red Winter Area*

About 85 per cent of the hard red winter wheat of the United States is grown in Kansas, Nebraska, Oklahoma, Texas, and Colorado, and more than 97 per cent of the wheat acreage in these five states is of this class. In addition, important acreages are grown in Montana, eastern Washington, eastern Oregon, southern Idaho, Missouri, and Illinois. It also constitutes an important segment of the wheat crop in Utah, Wyoming, New Mexico, southern South Dakota, and southern Minnesota, although the total acreage of winter wheat in these areas is relatively small. Eastern Kansas and western Missouri formerly were often considered as outside the hard red winter wheat belt, but in recent years new early-maturing varieties of hard winter wheat have replaced much of the acreage of soft red winter wheat that formerly predominated in this area. The discussion that follows will be limited to hard red winter wheat in the Great Plains and, unless otherwise indicated, to the five states in which most of it is grown.

a. Factors Affecting Choice of Varieties. The principal factors affecting the choice of varieties and breeding objectives are winterkilling, or the fear of winterkilling, especially in the more northern areas; drought and high summer temperatures especially in western Kansas, Nebraska, Oklahoma, eastern Colorado, and the Texas Panhandle; and quality. Resistance to leaf rust has been an important objective east

of the 100th meridian, and resistance to Hessian fly, especially in central and eastern Kansas and southeastern Nebraska. Stem rust occasionally causes severe damage, especially when the crop matures unusually late. Ordinary bunt has been present throughout the area, but most of the varieties now grown are relatively resistant. This, plus seed treatment, as recently pointed out by Melchers (1950), has kept losses at a low level in recent years. Dwarf bunt is important in central Montana. Foot rots, septoria leaf spot, mildew, scab, and mosaic in recent years have claimed much attention. Lodging is an ever-present hazard. Hard winter varieties are typically characterized by weak straw, and much lodging occurs in wet seasons, especially in the eastern part of the area. A few of the improved varieties are somewhat resistant to lodging, but efforts to produce stiff-strawed varieties that do not lodge easily have been less successful than in the Pacific Northwest. The greatly increased acreage of early-maturing varieties has re-emphasized the damage from late spring freezes—a problem that was recognized before 1900 but virtually disappeared with the advent of TURKEY and similar varieties. Better quality has been recognized as a most important objective especially in recent years.

b. Early Varietal Improvement. As we have seen, a very great improvement in varieties for the southern Plains was brought about near the close of the nineteenth century by the substitution of TURKEY for the soft red winter and spring wheats then grown. Without TURKEY and similar varieties, the expansion of winter wheat into Montana and the high dry southern Plains would not have been economically feasible. Clark and Martin (1925) have stated: "The introduction of hard red winter wheat into certain of these localities which had been abandoned by the earliest settlers later made possible a permanent wheat-growing industry."

Varietal improvement during the first ten to fifteen years of the twentieth century consisted mostly of conducting field trials to determine relative yields, winter hardiness, and other characteristics of the many collections Carleton and others had brought into the United States from Russia and other European countries around 1900. These trials at first included the more promising soft red varieties, but these were soon dropped at most stations because of obvious defects.

Results obtained from many of these early trials have been reported by Hume *et al.* (1915), Evans and Janssen (1922), Martin (1922), Towle (1925), Coffman (1925), Stoa (1926), Swanson (1927), May (1927), and Kezer *et al.* (1928). Those obtained in the drier areas during the period 1906–1922 have been summarized in considerable detail by Clark and Martin (1925).

As pointed out by Clark and Martin (1925), the yields of most of the varieties and strains compared in these early trials were very similar; "Few can be said to be significantly better than the others." Some, however, were found to be significantly poorer than the standard KHARKOF or than other strains. One practical result was to establish the identity of many of the various lots of TURKEY and KHARKOF then being grown and the superiority of a few of them. Another was to verify the superiority for most of the area of the better hard red winter varieties as compared with soft red winter.

c. Principal Achievements. Significant improvements, in addition to those just mentioned, during the past fifty years include the selection and distribution of (1) KANRED, by the Kansas Station in 1917; (2) BLACKHULL, by a private breeder, Mr. Earl G. Clark, of Sedgwick, Kansas, in 1917; (3) NEBRASKA NO. 60 in 1918, CHEYENNE in 1930, and NEBRED in 1938 by the Nebraska Station; (4) the breeding and distribution in 1932 of TENMARQ by the Kansas Station; and (5) the breeding and distribution in 1942 and later of several early-maturing varieties of unusual merit: PAWNEE, COMANCHE, TRIUMPH, WESTAR, and WICHITA. Others worthy of note but distributed too recently to have had any material effect on production are KIOWA, QUANAH, APACHE, PONCA, and SIOUX.

The selections of MONTANA NO. 36 and KARMONT and their distribution in 1915 and 1921, respectively, by the Montana Station are also worthy of mention as well as the distribution of the very winter-hardy, bunt-resistant variety YOGO in 1932 by the Montana Station. The production through hybridization of MINTURKI, MARMIN, and MINTER at the Minnesota Station and their distribution to farmers in Minnesota and other states in 1919, 1940, and 1946, respectively, should also be mentioned. None of these last-mentioned varieties is widely grown, but they are important in the particular areas in which they are grown. Another noteworthy development, although not an achievement in the minds of many people, were the selection and distribution of EARLY BLACKHULL. CHIEFKAN, and RED CHIEF; these varieties have found favor with many farmers but have been universally condemned by millers and bakers because of poor quality for bread.

Another very important achievement has been the incorporation of resistance to Hessian fly in the varieties PAWNEE and PONCA. The possibility of obtaining resistant varieties for this area apparently was never seriously considered until pointed out by McColloch and Salmon (1918).

Resistance to leaf and stem rust was considered an important characteristic of KANRED and has since been an important objective achieved in part in most of the varieties since distributed in the area. One of the

chief reasons for the cross between MARQUIS and a sister selection of KANRED from which TENMARQ was selected was to incorporate the quality characteristics of MARQUIS into a hard winter variety. Quality has been a high priority objective ever since.

The more important changes in varieties of hard red winter wheat in the southern Great Plains are shown in Fig. 19. It will be seen that in 1919 soft red winter wheats occupied about 16 per cent of the wheat area, most of the remainder being devoted to TURKEY. KANRED had replaced a considerable acreage of TURKEY by 1924 and then declined to less than

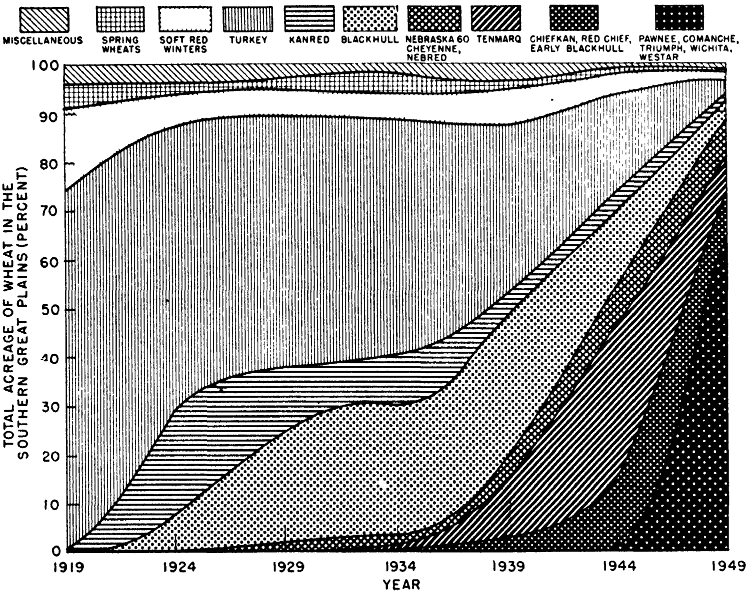

FIG. 19. Changes in the acreages of important varieties of wheat in the southern Great Plains (Kansas, Nebraska, Colorado, Oklahoma, and Texas) from 1919 to 1949.

2 per cent of the total area. KANRED made a phenomenal yield record at first, the average for an eight-year period at Manhattan, Kansas, exceeding that of TURKEY by 4.5 bushels per acre or about 20 per cent, and likewise in nearly 250 trials in other parts of the state. During the past twenty years it has outyielded TURKEY by only about 5 per cent. Its superior yields were thought to be due to greater winter hardiness, resistance to leaf and stem rust, and slightly earlier (one day) heading and ripening. New races of rust eliminated whatever advantage it had in rust resistance, and more extensive tests indicate only a very minor difference in winter hardiness. Its weak straw offsets any advantage it

may have gained from its earlier maturity, especially for the more humid areas.

BLACKHULL lasted somewhat longer than KANRED but eventually gave way to better varieties. It was less winter-hardy than TURKEY but it is doubtful if this has been an important factor in its demise, since winter-killing has not been an important factor in the area where BLACKHULL has been grown for thirty years or more. Probably its early maturity is the chief reason for the superior yield of BACKHULL and its persistence on farms.

TENMARQ was a very popular variety in Kansas and areas south of Kansas for a time, principally because of its relatively high yields, early maturity, relatively stiff straw, and good quality. It was unpopular in some sections because of a low test weight. Like its predecessors, it has been largely replaced by higher-yielding varieties.

NEBRASKA NO. 60, NEBRED, and CHEYENNE are grown extensively in Nebraska and eastern Wyoming. CHEYENNE is also grown in western Oklahoma and the northern Texas Panhandle, and NEBRED in South Dakota. In Nebraska these varieties have replaced about half of the TURKEY previously grown. NEBRASKA NO. 60, the first of the three to be distributed, is now grown on only a few thousand acres. All excel in winter hardiness, and CHEYENNE has stiffer straw and lodges less than any other TURKEY-type varieties. These three varieties are unimportant outside of the areas here mentioned.

CHIEFKAN and RED CHIEF are of interest primarily because farmers have insisted on growing them in spite of their poor quality for bread. They have done so largely because of the high test weights and fine appearance of the grain, stiff straw, and relatively high yields compared with TURKEY and KHARKOF, though they are less productive than some of the newer varieties. Their acreage increased quite rapidly for a time and then declined in favor of the earlier higher-yielding varieties.

PAWNEE, COMANCHE, TRIUMPH, WICHITA, and WESTAR are grouped together for this discussion because they are all very early or medium early, they have given phenomenally high yields, and they have increased in farmers' fields about as rapidly as seed supplies would permit. PAWNEE is resistant though not immune to Hessian fiy and has been credited with greatly reducing the losses from this insect in eastern and central Kansas and southeastern Nebraska.

(1) New varieties and increased production. Numerous yield trials both in field and nursery plots have been conducted at many stations throughout the Great Plains. Beginning with the co-ordinated co-operative program in the fall of 1930, a considerable number of varieties have been grown uniformly at selected stations. At practically all

stations TURKEY (CI 1442, formerly called KHARKOF) has been included as a standard variety for comparison since 1915. Results from some of these comparisons have been reported by Painter *et al.* (1931), Salmon and Laude (1932), Jodon (1932), Robertson *et al.* (1933), Kiesselbach *et al.* (1933), Carter (1939, 1944), Quisenberry *et al.* (1940), Robertson *et al.* (1942b), Reitz *et al.* (1943), Reitz and Laude (1943), Reitz and Heyne (1944), Laude *et al.* (1952), and Schlehuber *et al.* (1946). Mimeographed reports of the uniform tests have been prepared each year by Quisenberry (1931–1946, inclusive) and by Reitz (1947–1950, inclusive). These publications and reports have been used extensively in the discussion that follows.

The average yields compared with TURKEY (CI 1442 in all but a few cases) are summarized in Table XIV. Gains in yield for each variety over TURKEY are adjusted to an average yield level of 13.8 bushels per seeded acre in the same manner as was done for spring wheat. This table

TABLE XIV

Comparative Yields of TURKEY and Other Varieties of Hard Red Winter Wheat at Experiment Stations in the Great Plains *

Variety	Number of stations	Maximum years at stations	Number of station years	Average yield: TURKEY, (1442) bu./acre	Average yield: Variety named in column 1, bu./acre	Average gain over TURKEY, bu./acre	Gain adjusted to yield level of 13.8 bu., bu./acre
KANRED	12	39	206	23.7	24.7	1.0	0.0
BLACKHULL	12	30	196	23.1	24.8	1.7	0.7
TENMARQ	15	24	200	22.7	25.2	2.5	1.4
CHEYENNE	8	19	135	25.3	27.9	2.6	1.2
NEBRED	4	19	56	25.9	27.8	1.9	0.5
EARLY BLACKHULL	13	19	164	23.4	25.1	1.7	0.7
CHIEFKAN	9	13	84	22.4	25.9	3.5	2.3
RED CHIEF	13	10	104	23.0	25.7	2.7	1.5
WICHITA	13	11	107	23.0	26.8	3.8	2.5
PAWNEE	13	14	133	22.2	27.8	5.6	4.2
COMANCHE	13	14	139	22.0	26.8	4.8	3.5
TRIUMPH	7	8	37	23.8	26.0	2.2	1.0
WESTAR	9	7	51	22.3	26.3	4.0	2.7
KARMONT	2	17	33	23.5	23.9	0.4	0.0
YOGO	2	17	33	23.5	25.0	1.5	0.4

* The original data from which this table was prepared have been published and referred to in the text or were obtained in cooperation with the State Agricultural Experiment Stations of Nebraska, Kansas, Colorado, Oklahoma, and Texas.

includes results from field plots only, except for a few stations which in recent years have discontinued field plot comparisons and have substituted nursery plots replicated four to ten times. This table also includes data only from those stations located in the areas where the respective varieties were grown, as shown by Clark and Bayles (1951). For example, the averages for TENMARQ, BLACKHULL, PAWNEE, COMANCHE, TRIUMPH, WESTAR, EARLY BLACKHULL, RED CHIEF, and CHIEFKAN include results from no station north of Kansas, and conversely for CHEYENNE, from no station south of northern Texas and northern Oklahoma.

The acreages of those varieties grown on more than 250,000 acres in 1949 are given in Table XV, together with the estimated gain in yield over TURKEY and the estimated increase in production that may properly be attributed to each. These latter, it will be seen, total 91,116,000 bushels.

This estimate does not take into account the considerable acreage devoted to soft red winter which has been almost completely replaced by better-yielding varieties of hard red winter. The area in soft red winter and spring wheat in 1900 is not known but certainly was no less than in 1919, when these classes accounted for about 16.5 per cent of the acreage in the five principal hard red winter wheat states. They now comprise only about 2.5 per cent of the acreage, a difference of 14.0 per cent. As-

TABLE XV

Acreages of Important Varieties of Hard Red Winter Wheat in the Great Plains and Estimated Increase in Production Due to Each in Relation to TURKEY

Variety	Acreage in 1949	Estimated gain in yield, bu./acre	Estimated increase in production, bu.
PAWNEE	9,190,000	4.2	38,598,000
COMANCHE	5,932,000	3.5	20,762,000
TRIUMPH	5,596,000	1.0	5,596,000
WICHITA	3,004,000	2.5	7,510,000
TENMARQ	2,903,000	1.4	4,064,000
WESTAR	2,170,000	2.7	5,859,000
EARLY BLACKHULL	2,106,000	0.7	1,474,000
CHEYENNE	1,941,000	1.2	2,329,000
BLACKHULL	1,786,000	0.7	1,250,000
NEBRED	1,457,000	0.5	729,000
RED CHIEF	1,161,000	1.5	1,742,000
CHIEFKAN	425,000	2.3	978,000
YOGO	562,000	0.4	225,000
KARMONT	511,000	0.0	......
KANRED	252,000	0.0	......
Total			91,116,000

suming the same proportion in recent years would mean that hard red winter is grown on about 5,500,000 acres that now would be growing lower-yielding varieties of soft red and spring wheat, had no improvements been made. They have been replaced mostly by PAWNEE.

PAWNEE has not been directly compared with any of these soft red winter varieties experimentally, nor, in fact, have extensive trials comparing any varieties of hard and soft winter wheat been conducted in recent years. Salmon and Laude (1932) reported the results of 598 comparative trials of KANRED and FULCASTER on farmers' fields in eastern Kansas. The average difference was slightly (0.6 bushel) in favor of KANRED. Greater differences were reported for less extensive trials on experimental fields in southeast Kansas. Since FULCASTER was without doubt among the highest- or probably the highest-yielding variety of soft wheat grown in this area, it seems safe to conclude that the gains in yield due to PAWNEE are at least as great as those shown in Table XIV. This would mean an additional increase in production of about 23,000,000 bushels as a result of substituting PAWNEE for the soft wheats and other inferior classes grown before 1900, or a grand total of nearly 114,000,000 bushels.

This estimate, however, is based on the 1949 acreage, which is nearly 10,000,000 acres in excess of the average for the preceding ten years. Reducing the estimated increase proportionately brings the total down to 85,412,000 bushels. This indicates the probable gain in production over the varieties available in 1900, with weather, disease, and other conditions like those of the past twenty to thirty years. It does not take into account the probable increase in rust and other diseases had new varieties not been introduced nor the increased production due to expansion of wheat growing into drier, more hazardous areas. This latter is mostly due to improvements in cultural methods, to power equipment, and to varieties that were available before 1900 and presumably would eventually have been grown in these areas. Since stem rust has caused less damage than in the hard red spring wheat region, it is quite unlikely that new races and the build-up of inoculum on susceptible varieties would have been as important as in the hard red spring region.

Leaf rust is relatively more important than stem rust in the southern Plains. Probably a considerable part of the greater yield of PAWNEE, COMANCHE, and WESTAR are due to their resistance to this disease. New races that attack them are already in the area. This may mean that their yields, relative to TURKEY and other susceptible varieties, will decline.

There are perhaps other sound reasons for doubting whether the relatively large gains in yield recorded especially for PAWNEE and COMANCHE will be maintained over a long period of years. The maximum

length of the testing periods for these two are fourteen years at Lincoln, Nebraska; fourteen years for COMANCHE at Hays, Kansas; and thirteen years for PAWNEE at Manhattan, Hays, and Woodward. These are fairly long periods compared with the usual run of varietal tests but not very long in relation to year-to-year variations known to be characteristic of the area. Also the testing periods have not included long periods of extreme drought such as are known to occur.

(2) Quality and other characteristics. Improvements with respect to quality and other characteristics have been quite substantial, but lack of space precludes a detailed discussion. PAWNEE, the most extensively grown variety, is about equal to TURKEY with respect to all important quality characteristics, and COMANCHE is distinctly superior to TURKEY in gluten strength. WICHITA has better quality than EARLY BLACKHULL and has replaced much of the acreage of that variety. All of the new varieties released by the experiment stations of the area in recent years are far superior to such varieties as RED CHIEF and CHIEFKAN in most respects. Since they also produce as high or higher yields, they have replaced considerable acreages of them.

Extensive determinations of quality characteristics of numerous varieties and selections have been made in recent years. Some of the results have been reported by Finney and Barmore (1945, 1948), Fifield *et al.*, (1937), Barmore *et al.* (1937–1942), and Finney *et al.* (1948–1950).

Most of the new varieties have shorter straw and lodge less than TURKEY, have higher test weights, and are generally equal to or superior to TURKEY for most of the plant characteristics desired by farmers. The early and medium-early varieties, WICHITA, TRIUMPH, PAWNEE, COMANCHE, KIOWA, and PONCA, are slightly or somewhat less winter-hardy than TURKEY. This has limited the extensive use of them in western Nebraska and contiguous areas and, of course, may result in some losses in future years in the areas where they are now grown. There is, however, substantial evidence to indicate that the advantages derived from early maturity far offset the probable damage from this cause.

4. Improvement of Varieties for the Western United States

Wheat is grown under a wide variety of environmental conditions in the western United States. For the purpose of this discussion, three distinct areas may be recognized: (1) The Pacific Northwest, which includes Washington, Oregon, and northern Idaho; (2) the intermountain area, mostly Utah and southern Idaho; and (3) California. A few thousand acres are grown in Arizona, Nevada, western New Mexico, and western Colorado. Some is grown under irrigation. Numerous varieties of all market classes of wheat except durum are grown. Hard winter wheats

predominate in Utah and southern Idaho and are important in central and southern Washington. White wheats, including winters and springs and club and common varieties, are most important in eastern Washington, northeastern Oregon, and northern Idaho. Varieties of white spring wheat seeded, however, in the fall are grown almost exclusively in California. A large proportion of the acreage of the Western States is in Washington, Oregon, and northern Idaho, often referred to as the Pacific Northwest.

a. Varieties for the Pacific Northwest. Improvement of varieties for the Pacific Northwest during the past half century has revolved largely around the problem of resistance to bunt or stinking smut. Nowhere in the United States and probably nowhere in the world has bunt been so serious or so difficult to control. Previous to 1900 it seems to have been no less nor no more serious than elsewhere in the United States (Piper, 1893; Woolman, 1914). Soon after 1900 it was repeatedly observed that seed treatment often was ineffective no matter how carefully it was done. Richardson in 1911 suggested the possibility of soil infection by wind-blown spores, and Heald and Woolman (1915) and Woolman and Humphrey (1924) secured convincing evidence that such was the case, especially in the Palouse area of eastern Washington, northeastern Oregon, and northern Idaho. In this area a combination of dry summers, high and frequent winds during the threshing season, summer fallow, and fall seeding provided the conditions that made soil infection possible. Threshing machines broke up the bunt balls releasing billions of spores to be blown to fallow fields, there to lie dormant until fall rains germinated them with the wheat. It has been said (Woolman and Humphrey, 1924) that "during the season of a bunty year one might stand on a hill and see clouds of black dust rising from every threshing machine in sight and drifting off with the wind." Heald and George (1918) set out spore traps in each of two seasons, from the results of which they calculated that an average of five million or more spores were deposited on each square foot of soil surface. A dramatic feature was the threshing machine fires or explosions caused by static electricity igniting the clouds of spores. Roethe and Bates (1920) refer to an estimate of losses from this cause alone of $1,000,000 in 1914 and 1915. Bunt has been less serious in the Big Bend and lower Columbia basin areas partly because there is less soil infection, because much of the crop is seeded in the spring, and because the remainder consists largely of TURKEY and other varieties that are resistant to the races of bunt generally prevalent in this area.

Since the growing of resistant varieties is the only practical method of controlling bunt in infected soil, the breeding of resistant varieties has been an important feature of varietal improvement. Better quality and

resistance to lodging, to shattering, and to winterkilling have also been important objectives. Breeding for resistance to diseases other than bunt has been relatively unimportant. In no other section of the United States have wheat breeders been so successful in breeding short-strawed, lodging-resistant, high-yielding winter wheats.

The wheat variety picture in the area is greatly complicated by the presence of numerous varieties representing every market class except durum, and also by a great diversity of climate, especially precipitation and temperature. The annual precipitation, for example, in the wheat-growing areas ranges from an average of about 8 inches in the drier sections of the Horse Heaven and Big Bend sections to more than 25 inches in the eastern Palouse. In a discussion of varieties it is convenient to recognize three distinct areas: (1) the Palouse and foothill areas, which comprise southeastern Washington, northeastern Oregon, and northern Idaho; (2) the lower Columbia River Basin in south central Washington and north central Oregon on either side of the Columbia River; and (3) the Big Bend area of central Washington. These areas are not sharply delineated, however, because climate and varieties change gradually from one area to another.

The principal market classes now grown in the area are white wheat (including white club) and hard red winter. Soft red winter wheat is grown on a few thousand acres only. Hard red spring, chiefly MARQUIS, occupied about 12 per cent of the area in 1919 but has since declined to about 2.5 per cent.

White winter wheat, including both club and common varieties, predominates in the Palouse and Columbia basin areas, and white spring and hard red winter in the Big Bend areas. In these latter, the average acreages of hard red winter and white spring are roughly equal, although there is considerable fluctuation from year to year depending on whether fall rains are sufficient to germinate and establish a fall-seeded crop and on the degree of winterkilling. FEDERATION, a white spring wheat usually seeded in the fall, occupies a considerable acreage in the southern Palouse, principally south of the Snake River.

Outstanding achievements in the improvement of varieties for the area include: (1) the creation of the so-called Washington hybrids, which combined the winter hardiness of the better winter varieties with the stiff-strawed and nonshattering characteristics of the spring wheat grown before 1900; (2) the introduction of TURKEY wheat from the Midwest, in about 1900, one strain of which was found to be resistant to the bunt races prevalent in the Pacific Northwest prior to about 1930; (3) the introduction of BAART and of FEDERATION from Australia; (4) the breeding of the bunt-resistant varieties RIDIT, RIO, ALBIT, HYMAR, REX, and

ORFED; (5) the production of the short, stiff-strawed, high-yielding, excellent in quality, but bunt-susceptible variety, ELGIN; and (6) the selection of GOLDEN from GOLDCOIN. The production of the soft red winter variety, TRIPLET, from a complicated cross involving LITTLE CLUB, JONES FIFE, and TURKEY is also worthy of mention; as also are the two new varieties ELMAR and BREVOR, recently distributed to farmers. ELMAR combines the excellent quality of ELGIN with resistance to about one-half of the races of bunt found in the area, and BREVOR is the most resistant to bunt of any variety grown in the area. Both may be expected to increase rapidly as seed supplies become available.

None of the varieties of spring wheat grown extensively previous to the turn of the century is now important. The only ones grown at all are JENKIN, found on small acreages in the Yakima Valley, and PACIFIC BLUESTEM, found on a few thousand acres in the Big Bend area. None of the older winter wheats is grown with the possible exception of an occasional field of GOLDCOIN (then known as FORTYFOLD). HYBRID 128, the only one of the Washington hybrids that occupied a significant acreage as late as 1919, now is grown on less than 1.5 per cent of the total wheat acreage.

As for other areas, there is convincing evidence that the improved varieties are generally superior, in some respects far superior, to those they have replaced, although for various reasons it is difficult or quite impossible to determine accurately just what these improvements mean in terms of bushels of wheat or monetary returns to the farmers. Relative yields and other characteristics of varieties grown in the area compared in some cases with those grown previous to 1900 have been reported by Spillman (1909), Schafer and Gaines (1915), Gaines (1919, 1922, 1933), Gaines and Schafer (1932), Schafer *et al.* (1926), Barbee (1933), Vogel and Barbee (1944), Vogel *et al.* (1944, 1947, 1951), and Stephens *et al.* (1932). Annual mimeographed reports of the coordinated cooperative program of wheat improvement in the Western States have been prepared by Bayles (1931–1936, inclusive), Suneson (1937–1946), Bamberg (1947), and Vogel (1948–1950). Bayles (Anonymous, 1932) has summarized most of the experimental data obtained previous to 1931.

(1) White winter wheat. Important changes in varieties of white winter wheat in eastern Washington, eastern Oregon, and northern Idaho since 1919 are shown in Fig. 20. Since white winter wheats are grown principally in the Palouse and are the principal varieties there, this figure applies principally to the Palouse area and the transition zones surrounding the Palouse. Exceptions to this are the soft red winter varieties, JONES FIFE and RED RUSSIAN, which were grown on about 360,000 acres in 1919 but have since almost completely disappeared.

LITTLE CLUB was the most important variety in the area previous to 1900 and presumably for a time after 1900.

HYBRID 128 and to a lesser extent GOLDCOIN were first replaced by the bunt-resistant varieties ALBIT, HYMAR, REX, and ORFED, and these in turn by the short, stiff-strawed, popular, but bunt-susceptible varieties, ELGIN and ALICEL.

The varietal survey of 1949 reported about 344,000 acres of GOLDCOIN and 234,000 acres of GOLDEN for this area. The two varieties are very similar, and it seems certain that much of the reported acreage of GOLD-

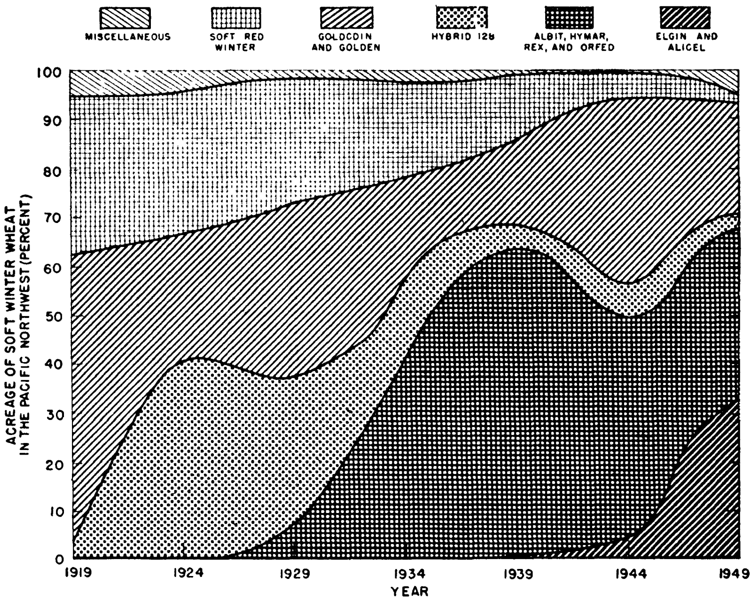

FIG. 20. Changes in the acreages of important varieties of soft winter wheat in the Pacific Northwest (eastern Washington, eastern Oregon, and northern Idaho) from 1919 to 1949.

COIN for recent years actually is GOLDEN. Vogel and Barbee (1944) state that most of the FORTYFOLD (GOLDCOIN) in Washington has been replaced by GOLDEN, and other competent observers since have found very little GOLDCOIN. GOLDEN shatters and lodges less than GOLDCOIN and in extensive experimental trials has on the average yielded about the same as HYBRID 128 or TURKEY and about 5 bushels more than GOLDCOIN.

Concomitant with the changes from bunt-susceptible to bunt-resistant and then again to bunt-susceptible varieties, there was first a marked decrease in bunt and then a marked increase, as shown by Salmon and Bayles (1952). This is an excellent illustration of the fact that disease-

resistant varieties are not likely to be grown by farmers unless they are acceptable in other respects or until the disease causes so much damage it cannot be ignored.

Of the bunt-resistant white winter varieties, ALBIT, HYMAR, REX, and ORFED, only the two latter have consistently yielded more than the varieties they have replaced or were expected to replace. REX has produced consistently high yields wherever it has been grown. ORFED also has generally produced good yields but has sometimes been injured by severe winters. Both excel in bushel weight, but REX, unfortunately, is deficient in milling qualities and sometimes takes a discount on the market.

The variety FEDERATION was grown on about 460,000 acres in 1949, principally from fall seeding, in the area south of the Snake River. In extensive experimental trials conducted for many years in the areas where it is generally grown or is promising, it has given higher average yields than TURKEY or HYBRID 128. The principal reason for the rapid increase of ALICEL and ELGIN are relatively high yields and short stiff straw, which will be discussed later.

(2) Hard red winter varieties. The first bunt-resistant variety for the area produced by hybridization was RIDIT, a hard red winter wheat, first distributed by the Washington Station in 1923. It is the result of a cross between TURKEY and FLORENCE. It has generally yielded less than TURKEY and consequently has not been grown extensively. ORO and RIO, both selected from TURKEY or from similar varieties at the Moro, Oregon, Station, have yielded about the same as TURKEY. ORO has not been popular with farmers, probably because of the tendency, as pointed out by Vogel and Barbee (1944), for the heads to snap off in high winds. The reported acreage of RIO in 1949 was only about 10 per cent of the hard red winter wheat acreage in the area. There are reasons, however, to believe that farmers generally do not distinguish it from TURKEY and that much of the acreage reported as TURKEY actually is RIO.

About 40,000 acres of WASATCH are now grown in the dwarf bunt-infected area of central Washington. It yields no more than TURKEY where dwarf bunt is not a factor, but, because of its resistance to this disease, has materially reduced losses in this area. The characteristics of WASATCH and its history are discussed later.

(3) Varieties of white spring. The principal improved varieties of white spring wheats are FEDERATION, which has been discussed above; BAART, which is grown principally in the Big Bend area; and IDAED, grown mostly in northern Idaho and the Palouse area of Washington. The two latter varieties occupied about 350,000 and 167,000 acres, respectively, in 1949.

BAART was introduced into the United States by the United States

Department of Agriculture in 1900 from Australia, to which it probably came originally from South Africa. It was first distributed to farmers in Arizona by the Arizona Station before 1914 and was first grown in the Pacific Northwest in 1917. It has largely replaced PACIFIC BLUESTEM in recent years. It heads and ripens earlier than PACIFIC BLUESTEM and produces better yields. At the Lind Station in central Washington it has averaged about 1 bushel per acre, or 5 per cent, more than PACIFIC BLUESTEM. IDAED is a result of selection from a cross made at the California Station, and was distributed by the Idaho Station in 1938. It matures early and does relatively well on shallow soils or from late spring seeding. MARFED, released to growers in 1946 by the Washington Station, is a promising variety for easten Washington, where it may replace some of the acreage of spring-sown FEDERATION.

(4) Soft red winter varieties. The only improved variety of soft red winter wheat grown in the area is TRIPLET, distributed by the Washington Station in 1918. It is a high-yielding variety, producing, on the average of all experimental trials, 2 bushels per acre more than TURKEY and 3 bushels more than HYBRID 128. It has never been popular, however, largely because of its pubescent chaff and the resulting discomfort to workers in harvesting and threshing. It was grown on only about 40,000 acres in 1949, principally in Washington.

(5) Relative yields. The changes in varieties mentioned above are to a considerable extent a reflection of relative yields as well as of resistance to lodging and to bunt. Yield trials in the area have been carried out mostly at the Washington Agricultural Experiment Stations at Pullman and Lind; at the Sherman Branch Station and the Pendleton Branch Station of the Oregon Agricultural Experiment Station; and at the Idaho Agricultural Experiment Station at Moscow. Additional trials have been conducted on private farms near Pomeroy and Walla Walla, Washington, and at several points in the Columbia River Basin of Oregon.

Wheat breeders in the area have depended to a large extent on nursery plot as well as field plot trials for determining yields and other characteristics of varieties. In general, the results from field plot and nursery trials have agreed remarkably well. HYBRID 128 or TURKEY have been used as standard varieties for comparison in both field plot and nursery trials.

The yield results from these trials have been summarized and are presented in Table XVI, primarily for the purpose of measuring the progress that has been made since 1900. For this reason, varieties that were important before about 1900, here designated as old varieties, are listed first. Since these have not usually been grown in direct compari-

son with the new varieties, they are compared first with HYBRID 128 or TURKEY, and then HYBRID 128 and TURKEY are compared with newer varieties. The table includes results both from field plot and from replicated three-row nursery trials. The number of comparisons shown in column 2 often exceeds the number of station years shown in column 3, because both field plot and nursery plot trials sometimes were conducted at the same station during the same years. The next to the last column shows the average gain in yield in experimental trials compared with HYBRID 128 or with TURKEY, whichever was used. The last column shows the estimated gain in farmers' fields obtained by adjusting the gains in experimental plots to the average yield level for the three states, as was done for hard red spring wheats.

Probably most interesting and significant are the relative yields of HYBRID 128 and the old varieties LITTLE CLUB, RED RUSSIAN, JONES FIFE, and GOLDCOIN, and in turn the relative yields of the new variety ELGIN as compared with HYBRID 128 and TURKEY.

LITTLE CLUB, which, according to Spillman (1909), was grown more extensively than any other variety in the higher rainfall areas before 1900, produced on the average 5.2 bushels per acre less than HYBRID 128; and RED RUSSIAN, also an important variety before 1900, averaged 4.7 bushels less than HYBRID 128. It is interesting to note that Spillman (1909, p. 25) estimated that the Washington hybrids would yield about 5 bushels per acre more than RED RUSSIAN. JONES FIFE and GOLDCOIN averaged 3.1 and 6.5 bushels per acre less than HYBRID 128. Taken together, all of the old varieties averaged 4.9 bushels less than HYBRID 128. The winter wheats, RED RUSSIAN, JONES FIFE, and GOLDCOIN, shatter badly in farmers' fields, whereas HYBRID 128 does not. Since experimental plots are generally harvested before shattering losses occur, the relative yields cited above do not take this factor into account.

ELGIN has been included in numerous experimental trials since it was selected from ALICEL at the Pendleton, Oregon, Station in 1932. The average gain is 8.1 bushels per acre as compared with HYBRID 128 and 7.7 bushels per acre compared with TURKEY, or an estimated gain over the old varieties of 13.0 bushels per acre. Also significant is the fact that ELGIN has yielded more on the average than HYBRID 128 or TURKEY wherever is has been tried in this area. This is an impressive record in view of the number and diversity of the experimental trials on which it is based.

The production of ELGIN has a significance beyond its practical use in the Pacific Northwest. Previous to the creation of ELGIN, it was often believed that short stiff-strawed varieties could be obtained only with some sacrifice in yield. ELGIN proves conclusively that this is not true

TABLE XVI

Relative Yields of Important Varieties in Field Plot and Nursery Plot Trials in the Pacific Northwest *

Item	Number of trials	Number of station years	Average yields: HYBRID 128, bu./acre	Average yields: TURKEY (1442), bu./acre	Average yields: Variety named in Column 1, bu./acre	Average gain over HYBRID 128 or TURKEY in experimental trials, bu./acre	Gain adjusted to average yield levels, bu./acre
Old varieties							
LITTLE CLUB	36	29	42.8		37.6	—5.2	
RED RUSSIAN	42	35	43.2		38.5	—4.7	
JONES FIFE	38	31	42.8		39.7	—3.1	
GOLDCOIN	74	31	36.0		29.5	—6.5	
AVERAGE						—4.9	—3.9
TURKEY	74	55	36.2		34.9	—1.3	—0.4
New varieties							
RIDIT	34	34	41.4		39.1	—2.3	—1.0
RIDIT	36	36		33.9	32.6	—1.3	—0.6
TRIPLET	77	69	37.0		39.0	+2.0	+0.7
TRIPLET	111	88		34.9	37.9	+3.0	+1.8
ALBIT	38	31	40.1		40.2	+0.1	0.0
HYMAR	32	24	43.1		43.9	+0.8	0.0
HYMAR	85	75		38.3	39.7	+1.4	0.0
RIO	45	25	41.2		42.3	+1.1	0.0
RIO	97	72		32.8	33.2	+0.4	0.0
GOLDEN	40	32	45.1		44.1	+1.0	0.0
GOLDEN	122	94		37.1	37.5	+0.4	0.0
REX †	51	44	40.9		43.2	+2.3	+0.6
REX	63	51		37.9	41.6	+3.7	+2.1
FEDERATION	34	18	38.2		40.6	+2.4	+0.9
FEDERATION	70	59		28.2	30.0	+1.8	+1.4
WASATCH	24	24		39.3	38.3	—1.0	0.0
ALICEL	16	16	38.9		43.4	+4.5	+2.8
ALICEL	36	21		23.1	27.1	+4.0	+3.9
ELGIN	15	15	44.1		52.2	+8.1	+5.5
ELGIN	67	60		38.6	46.3	+7.7	+5.7
ORFED	11	8	47.6		53.9	+6.3	+3.5
ORFED	31	31		37.9	41.3	+3.4	+1.9

* The original data from which this table was compiled have been published and are referred to in the text or have been obtained in cooperation with the State Agricultural Experiment Stations of Washington, Oregon, and Idaho.

† REX M_1 included.

in the Pacific Northwest and for this area, at least, has done much to determine the objectives of varietal improvement for the future. Hereafter, no variety for the Pacific Northwest can be expected to be endorsed enthusiastically by farmers unless it has short stiff straw similar to or better than that of ELGIN.

(6) Improved varieties and increased production. Estimates of the acreage of the leading improved varieties in eastern Washington, eastern Oregon, and northern Idaho, together with the estimated gains for each, and the total estimated increase in total production for each are presented in Table XVII. As for other areas, certain assumptions are made that cannot be verified; hence, considerable allowance should be made for error. The estimated gains in yield per acre shown in column 3 were obtained by adding the gains of HYBRID 128 over the old varieties shown in the last column of Table XVI to the average gains (if any) of the improved varieties over HYBRID 128. An exception is BAART, for which the average indicated gain is the estimated gain over PACIFIC BLUESTEM for the area in which BAART is generally grown. The gain for IDAED is assumed to be the same as for FEDERATION, since the yield of IDAED and FEDERATION have been substantially the same in experimental trials. Estimates of acreage in this table were calculated from those reported by Clark and Bayles (1951) by subtracting from the reported acreage those of certain varieties known not to be grown in the area.

This table indicates a total increase in production of nearly 20,000,000

TABLE XVII

Estimated Increase in Production of Wheat in the Pacific Northwest Due to Improved Varieties

Variety	Estimated acreage, acres	Estimated gains, bu./acre	Estimated increase in production, bu.
TURKEY	843,000	3.5	2,951,000
ELGIN	595,000	9.4	5,593,000
FEDERATION	463,000	4.8	2,222,000
REX	423,000	4.5	1,904,000
BAART	349,000	1.0	349,000
HYMAR	266,000	3.9	1,037,000
ALICEL	234,000	6.7	1,568,000
GOLDEN	234,000	3.9	913,000
ORFED	182,000	7.4	1,347,000
IDAED	167,000	4.8	802,000
RIO	115,000	3.9	449,000
HYBRID 128	77,000	3.9	300,000
Total			19,435,000

bushels that may properly be attributed to new varieties. It seems likely that the increase in production greatly exceeds this amount. Without much doubt the reported acreage of GOLDCOIN is really GOLDEN, which means there should be added to the above about 1,334,000 bushels, making a total increase of 20,769,000 bushels. Also, this estimate does not take into account the greater loss from shattering and from bunt undoubtedly suffered in farmers' fields as compared with experimental plots. Actually, the value of the bunt-resistant varieties to farmers probably far exceeds that indicated in the table; not only for this reason but also because they, without doubt, have materially reduced the amount of inoculum that would otherwise have been produced to infect all varieties. This would be difficult to prove and it would be even more difficult to estimate the effects, but that it is a fact to be considered can scarcely be doubted. On the other hand, these estimates do not take into account the opportunity to salvage some of the loss from winterkilling by reseeding in the spring. This could be important in particular seasons but probably is not significant over a long period of years.

b. Varieties in California. Wheat varietal improvement in California is unique in that backcrossing has been used almost exclusively to add desirable genes to existing varieties since about 1920. By this means, resistance to prevailing races of stem rust, bunt, and Hessian fly, singly or in combination, have been added to practically all varieties now grown on a commercial scale in the state. In 1949 these improved varieties occupied more than 85 per cent of the total wheat acreage of the state. Of special interest from a technical point of view and also important practically for those farmers directly concerned is the production of BIG CLUB 43, which combines in one variety stem rust resistance from HOPE, bunt resistance from MARTIN, and Hessian fly resistance from DAWSON. So successful has this been that the use of these varieties in the Montezuma hills region has so completely eliminated Hessian fly that inheritance studies conducted there had to be abandoned. Other varieties that are resistant to Hessian fly are POSO 44 and POSO 48.

Backcross-derived new varieties are substantially like the commercial (recurrent) parent in all respects except for the specific characters that have been transferred to them. Consequently extensive testing for yield and other characteristics is usually less necessary, and farmers can substitute the new pest-resistant variety for the old type with reasonable assurance that defects with which they are unfamiliar are not likely to appear. The distribution of the new varieties is facilitated by designating them with the name of the original variety and a numeral suffix indicating the year in which they were released for distribution. Suneson

(1947) and Suneson and Briggs (1941) have reported the results of this work in detail.

Early in the century, PACIFIC BLUESTEM was grown in California more extensively than any other variety. SONORA was an important variety, as also were LITTLE CLUB and BIG CLUB. BAART was introduced soon after 1914, and accounted for more than 30 per cent of the acreage by 1924. In 1949 the leading varieties were WHITE FEDERATION 38, RAMONA 44, and BAART 38, with only small remnants of their prototypes. Thus, during the half century, there has been both a widespread displacement of old varieties and recently a substitution of disease-resistant forms for the newer varieties.

Experimental data for a nineteen-year period at Davis, and for a large number of trials in farmers' fields over an eleven-year period, as reported by Suneson and Briggs (1941), leave no room for doubt respecting the superior yield of the improved varieties. BAART at Davis has averaged about 9 bushels per acre more than PACIFIC BLUESTEM and BIG CLUB. Equally favorable yields were recorded when these were compared with WHITE FEDERATION, FEDERATION, RAMONA, ESCONDIDO, BUNYIP, ONAS, and POSO—all varieties that have at one time or another been grown more or less extensively in the state. Suneson (1947) has published comparative yields of BAART and BAART 38 for a six-year period at Davis, where rust was assumed to be a yield factor. BAART had considerable rust in some years, whereas BAART 38 was practically free of rust. BAART 38 on the average yielded 4.9 bushels more than BAART. Suneson (1947), Suneson and Briggs (1941), and Suneson *et al.* (1941) have reported the results of several nursery tests on California farms. In these tests BAART 38 has averaged a fraction of a bushel to 2.0 bushels or more in excess of BAART and yielded the same as BAART in the absence of stem rust and bunt. It is doubtful, however, if sufficient tests have been conducted to show what gain in yield can reasonably be expected over a period of years.

Accepting the yield record at Davis as fairly representative of the wheat-growing areas of the state and reducing the average gain for BAART and other varieties over PACIFIC BLUESTEM, LITTLE CLUB, and others to that expected at the average yield level of the state would mean an average increase in yield of about 4 bushels per acre. It seems reasonable to assume that BAART 38 would add another bushel to the gain and also that the gains for other new improved varieties are comparable to those of BAART 38. An average gain of 5 bushels per acre applied to the 85 per cent of the California acreage on which these varieties are grown would mean an additional annual production of roughly 3,000,000 bushels per year.

c. Varieties in the Intermountain Areas. Wheat occupies an important niche in the agricultural economy of much of the intermountain area, including the Great Basin and many intermountain valleys. The principal acreage is in southern Idaho and northern Utah. Most of the wheat grown in the intermountain area is hard red winter; white spring varieties predominate on irrigated land.

Wheat breeding in the area is of special interest in relation to dwarf bunt. Nowhere in the United States has dwarf bunt caused so much damage, and nowhere has so much been done to control it. The only known effective and practical control method is to breed resistant varieties, and the Utah Agricultural Experiment Station has taken the lead in producing them. Three such varieties produced by the Utah Station in cooperation with the United States Department of Agriculture have been released to farmers. They are RELIEF, produced from a HUSSAR × TURKEY cross and first grown by farmers in the fall of 1932; CACHE, from a RIDIT × UTAH KANRED cross, distributed to farmers in 1937; and WASATCH, from a RELIEF × RIDIT cross, first released to farmers in 1942. These three varieties accounted for about 200,000 acres or 58 per cent of the hard red winter wheat in Utah in 1949 and nearly 260,000 acres or 40 per cent of the hard red winter wheat grown in Idaho. About 40,000 acres are grown in central Washington and a similar acreage in central and western Montana, in both of which areas dwarf bunt has been a serious threat.

Excepting CACHE, which is beardless, these varieties are very similar in essential respects to other hard red winters. They yield about the same as the better varieties in the absence of dwarf bunt. Since experimental yield trials are usually conducted on bunt-free or nearly bunt-free soil, comparative yields in these trials do not reflect their real worth to growers. There can be no reasonable doubt as to their value in reducing losses from dwarf bunt. Tingey and Woodward (1935) and Woodward and Tingey (1944) have given interesting accounts of the breeding of RELIEF and CACHE, respectively, including data relating to yield, quality, resistance to various races of bunt, and other characteristics.

Significant improvements in varieties of white spring wheat for irrigated farms have also been made. DICKLOW, selected by a farmer from a field of SURPRISE, was distributed in southern Idaho in 1912 or 1913. A more uniform type selected from DICKLOW and known as IRWIN DICKLOW has since replaced a considerable part of the original type. The principal variety now grown under irrigation in southern Idaho and in Utah is LEMHI, which was selected from a cross between FEDERATION and DICKLOW at the Aberdeen Branch Station in southern Idaho and dis-

tributed to farmers in 1939. In experimental trials under irrigation, it has outyielded all older varieties and is highly regarded by millers because of the excellent quality of pastry flour produced from it.

d. Quality of Western Wheats. A consideration of the improvement of varieties of wheat for the Western States would be incomplete without some mention of quality. The subject is too complex to discuss in detail in the space available. Nearly every market class of wheat is represented by from a few to several varieties, and the crop is used for bread and for pastries, including special-purpose flours.

The great need for varieties resistant to bunt and the lack until recently of adequate facilities and techniques for testing quality characteristics has resulted in the distribution of a few varieties with less desirable quality characteristics than under different circumstances would be permissible. Among such varieties are REX and BREVOR, which are somewhat deficient in milling quality, and RELIEF and CACHE, which are slightly inferior to other hard winter varieties in bread characteristics. On the other hand, the introduction of TURKEY early in the century certainly resulted in considerable improvement in the quality of the crop for bread, as also did the introduction of BAART in about 1915. Most of the new varieties released during the past quarter century are definitely superior in test weight and flour yield. Possibly the most important advances relating to quality during the past fifty years are the better understanding of quality factors and the development of better methods and techniques for measuring quality.

Results of milling, baking, chemical, and physical studies of the grain and flour of many varieties and selections of wheat grown in the western United States have been reported by Fifield *et al.* (1945, 1950, 1936–1948) and by Barmore *et al.* (1947–1951).

5. *Improvement of Varieties for the Eastern United States*

It is well known that soft winter wheats predominate in the eastern United States, here defined as the area east of Texas, Oklahoma, Kansas, Nebraska, and the Dakotas, but excluding Minnesota. Actually, most of the crop in Iowa is hard red winter wheat, as is also approximately half that in Missouri and nearly half of that in Illinois. Less than one-fourth of the Wisconsin acreage is soft winter wheat, the remainder being mostly hard red spring wheat. The climate of these states is not suitable for the production of high quality hard wheat, and this area might more properly be considered a transition zone. Considerable shifts from hard red winter to soft red winter wheat and vice versa take place from time to time depending on weather, diseases, and winterkilling, and on relative yields and prices of available varieties of each class. During

the mid-twenties and early thirties, for example, 90 per cent or more of the Missouri wheat acreage was soft red winter wheat. Drought in 1934 and 1936, a severe stem rust epidemic in 1937, and severe winterkilling in certain sections in 1938 (Poehlman and Bowman, 1945) caused a considerable shift to the more resistant hard red winter wheats; this shift was accentuated by the introduction of PAWNEE into the area in about 1943 and by the relatively high prices for hard red winter in recent years.

Soft red winter wheat constitutes 97 per cent or more of the total wheat acreage in all of the remaining Eastern States except New York and Michigan. In 1949 more than 96 per cent of the New York wheat acreage and nearly 87 per cent of that in Michigan was soft white winter wheat.

Wheat grown in the eastern United States is usually low in protein content regardless of class or variety. Soft wheat is especially suitable for pastries such as cakes, cookies, and crackers and is satisfactory for bread if blended with high protein hard wheats or if high in protein because of season or the conditions under which it is grown.

Rainfall is relatively high, and wet weather diseases such as leaf rust, scab, mildew, and septoria cause much damage. Stem rust occasionally causes severe damage but usually only in limited areas. Most of the varieties are relatively early and thereby avoid much damage that would otherwise occur. Lodging is often important, although most varieties have relatively stiff straw. Winterkilling sometimes causes severe losses, as in 1928 when approximately 62 per cent of the seeded acreage in Illinois, Indiana, and Ohio was abandoned.

Ordinary bunt and loose smut are widely prevalent, but losses are usually held to a low level by seed treatment or resistant varieties. Dwarf bunt is present in a small area in western New York. Mosaic was discovered in central Illinois, and flag smut in southern Illinois and eastern Kansas in 1919. Mosaic has been a constant threat throughout much of the area since but has been kept under control in most areas by the use of resistant varieties.

Resistant varieties also have apparently eliminated the flag smut, since it has not been seen for a number of years. Hessian fly has been a more or less constant menace to the crop since revolutionary days but for the most part has been kept under control by cultural methods, timely seeding, and to a slight extent by resistant varieties. Severe damage has occurred in some areas and in some seasons. Jointworm causes considerable loss mostly in Ohio and adjacent areas and appears to be moving westward, according to Jones *et al.* (1952). The nematode disease of wheat sometimes causes severe local losses in Virginia, the Carolinas, and Georgia.

a. Early Improvement in Varieties. There was much interest in the improvement in varieties previous to 1900, mostly on the part of farmers or farmer–seedsmen with a flair for wheat breeding. Among the important varieties produced in this period by plant or head selection from existing varieties were ZIMMERMAN, FULTZ, MEALY, CURRELL, GOLDCOIN, HARVEST QUEEN, PENQUITE, RUDY, GREESON, and DAWSON, the latter having been selected by a Canadian farmer and introduced into the United States. Hybridization resulted in such varieties as FULCASTER, JONES FIFE, GENESEE GIANT, and probably DIEHL-MEDITERRANEAN, and FULTZO-MEDITERRANEAN. LEAP, RED WAVE, and ILLINI CHIEF logically belong to this period, although not grown by farmers until after 1900.

By 1919, when the first wheat varietal survey was made, these improved varieties had replaced one-third or more of the acreage of the older ones. The more important were FULTZ (4,800,000), FULCASTER (2,576,000), RED WAVE (1,132,000), and GOLDCOIN (947,000 acres). RED WAVE is of academic interest today because it was one of the first to be recognized as having poor quality. ILLINI CHIEF appears to be an older variety renamed and advertised as resistant to Hessian fly. This claim, like similar ones with respect to MEDITERRANEAN and DAWSON, was largely discounted until verified by controlled experimental trials during the past twenty-five or thirty years.

The state agricultural experiment stations of the region and the United States Department of Agriculture took a very active part in wheat improvement immediately after they were organized. Wheat was then actually and relatively a much more important crop than it is now and even before the establishment of our present system of experiment stations under the Hatch Act, several agricultural colleges were actively engaged in wheat improvement. Seed companies have also taken an active part.

Efforts by the experiment stations to improve varieties were for many years almost entirely limited to comparisons of yield and other characteristics of the many varieties then available, including such related questions as to the relative yields of bearded and beardless varieties, whether varieties deteriorate or "run out," whether mixtures are better than a single variety, the use of the fanning mill, and the relative value of large and small kernels for seeding.

Hundreds of varieties that had been introduced from foreign countries or selected by farmers were compared during the first twenty or twenty-five years after the stations were established. Latta (1900), for example, states that 178 varieties of winter wheat and 11 varieties of spring wheat had been tested by the Purdue Agricultural Experiment

Station by 1900, and Schmitz (1916) states that the Maryland Station tested 300 varieties between 1895 and 1916.

Around 1910 the Ohio Station was using 400 tenth-acre plots in a four-year rotation or 100 plots each year for variety tests of wheat. Every Eastern State, except some of the New England States, Florida, and perhaps one other Southern State, has conducted variety tests of wheat, most of which have been extensive. The results of most of the early comparisons were reported by Waters (1891), Conner (1893), Garman (1898), Latta (1900), Watson and Hess (1901), Wiancko and Fisher (1906), Hume *et al.* (1908), Scherffius and Woosley (1908), Noll (1909, 1917), Schmitz (1910, 1916), Roberts and Kinney (1911), Nelson and Osborn (1915), Garren (1915), Williams (1916), Grantham (1918), Cauthen (1918), Stark (1931), Kemp and Metzger (1928), and McClelland (1932, 1946).

As in other areas, the improvement of existing varieties enlisted the interest of the stations at about the end of the century. Mass selection and continuous selection using the centgener method developed by Willet M. Hays of Minnesota was practiced at first. This soon gave way to pure-line selection and finally to hybridization.

b. Recent Achievements. Between 1900 and the present time about 90 new and improved varieties for the Eastern States, developed mostly by state stations alone or in cooperation with the United States Department of Agriculture, have been distributed to farmers. Most of the varieties now grown in the Eastern States have recently been described by Bayles and Taylor (1951). The most important ones in terms of 1949 acreages are THORNE (3,448,000 acres in 1949), YORKWIN (1,089,000), CLARKAN (847,000), FAIRFIELD (691,000), REDHART (604,000), VIGO (452,000), CORNELL 595 (336,000), TRUMBULL (301,000), FULHIO (178,000), SANFORD (165,000), FORWARD (140,000), HARDIRED (110,000), and NITTANY (110,000), all grown on 100,000 acres or more in 1949.

THORNE is a remarkable variety. To paraphrase a recent commentator and adapt his statement to the region as a whole, it is susceptible to most of the important diseases in the area and yet has established itself as the best all-round variety for much of the soft red wheat area. It was produced by the Ohio Station from a PORTAGE (selection from POOLE) × FULCASTER cross and distributed to farmers in 1937. Actually, it is resistant to many races of loose smut and to mosaic but very susceptible to leaf rust, stem rust, and scab. Its popularity among farmers is due principally to its stiff straw and high yields. Millers like it for the excellent soft qualities of its flour. Test weights of the grain are usually less than for other varieties.

It is grown most extensively in Ohio, Pennsylvania, northern Mary-

land, and Delaware with scattered areas in Indiana, southern Illinois, and Tennessee, Virginia, and West Virginia. Extensive tests throughout this area, including many stations in Ohio, for fifteen to twenty years have demonstrated its ability to yield well in spite of most diseases other than stem rust. Stem rust has not been generally prevalent in the area for many years.

YORKWIN and CORNELL 595, produced by the New York Cornell Station, are relatively even more important in New York and Michigan than THORNE is in Ohio or other Eastern States. Both are soft white winter varieties. YORKWIN is from a cross DIETZ (FULCASTER) × GOLDCOIN and CORNELL 595 from a complex cross involving HONOR taken twice, FORWARD, and NURED. NURED is the result of a cross between FORWARD and DIETZ. YORKWIN was distributed to New York farmers in 1935 and CORNELL 595 in 1942. They increased rapidly and occupied 94 per cent of the acreage of all wheat in New York and 73.3 per cent of all in Michigan by 1949. Both are characterized by stiff straw, winter hardiness, and good pastry quality. YORKWIN is resistant to several races of loose smut and CORNELL 595 to some races of loose smut, mildew, and septoria leaf spot. Both are susceptible to leaf and stem rust. Because of these varieties, soft red winter wheat and other classes have practically disappeared in New York, and their acreage has been greatly reduced in Michigan, thereby insuring a supply of more uniform wheat to millers.

CLARKAN was distributed by Mr. Earl G. Clark of Sedgwick, Kansas, the originator and distributor of the hard red winter varieties BLACKHULL, CHIEFKAN, and RED CHIEF. The original plant was found in a field of BLACKHULL and is presumed to have been the result of a natural hybrid between BLACKHULL and HARVEST QUEEN. It has become an important variety especially in Missouri. CLARKAN is characterized by rather tall but stiff straw, high test weight grain, and susceptibility to loose smut, mosaic, leaf, and stem rust. Its quality is acceptable, but the grain is somewhat harder and the gluten somewhat stronger than is characteristic of the better quality soft wheats.

FAIRFIELD and VIGO are examples of successful planned breeding to produce varieties of desired characteristics by hybridization. Both were produced at the Purdue Agricultural Experiment Station and were distributed to farmers in 1942 and 1946, respectively. FAIRFIELD, derived from a cross of PURKOF × FULHIO, inherited the winter hardiness of the former and the quality of the latter. It has replaced much of the PURKOF formerly grown in northwest Indiana. A leaf rust-resistant selection from FULTZ crossed with TRUMBULL resulted in VIGO. VIGO is resistant to many races of leaf rust and has the excellent quality characteristics of TRUMBULL. Both are resistant to mosaic, to some races of loose smut,

and relatively winter-hardy. Neither is resistant to bunt, scab, or stem rust.

SANFORD was first distributed to farmers in Georgia in 1940 and in 1949 occupied 72 per cent of the wheat acreage of that state. It was produced at the Georgia Station by backcrossing KANRED × PURPLESTRAW, using PURPLESTRAW as the recurrent parent while selecting for resistance to leaf rust. It is one of the few examples of the successful use of backcrossing in the Eastern States. It and its synonym SANETT are grown also to a limited extent in South Carolina. As would be expected from its origin, it is every similar to PURPLESTRAW in plant and grain characteristics. CHANCELLOR, also produced at the Georgia Station from a complicated cross involving backcrossing to PURPLESTRAW, has replaced much of the acreage formerly grown to SANFORD and SANETT. It was first distributed to growers in 1947.

HARDIRED was developed by the Coker's Pedigreed Seed Co. of Hartsville, South Carolina, from a cross involving HOPE, HUSSAR, and FLINT supplied by the United States Department of Agriculture. It was distributed by that company in the fall of 1940 and was grown on about 110,000 acres in 1949, mostly in South Carolina and North Carolina, with a few thousand acres each in Missouri, Virginia, Mississippi, and Georgia. Its acreage is probably much less than would otherwise be the case because of susceptibility to mildew. Like most varieties in the southern United States it is not a true winter variety and is not sufficiently winter-hardy for growing north of its present area of production.

Several other varieties worthy of mention are not grown extensively either because they are not widely adapted or because they have been so recently distributed that seed supplies have been limited or farmers are not acquainted with them. These are: MICHIKOF, PURKOF, and PURDUE No. 1, distributed by the Indiana Station in 1920, 1924, and 1934, respectively; BERKELEY ROCK and BALDROCK, by the Michigan Station in 1922 and 1931, respectively; VALPRIZE, NURED, and GENESEE, by the New York Cornell Station in 1931, 1939, and 1951, respectively; BLACKHAWK, by the Wisconsin Station in 1944; IOHARDI, by the Iowa Station in 1948; BUTLER and SENECA, by the Ohio Station in 1947 and 1950, respectively; PENNOLL, by the Pennsylvania Station in 1950; SALINE, by the Illinois Station in 1952; ATLAS 50 and ATLAS 66, by the North Carolina Station in 1948; COASTAL and COKER's 47–27, by the Coker's Pedigreed Seed Co., in 1949 and 1950, respectively; ANDERSON, by the South Carolina Station in 1951; and PURCAM, produced at the Purdue University Station but distributed by the South Carolina Station in 1951.

MICHIKOF, PURKOF, and BLACKHAWK are of interest because of their relation to the problem of quality in wheat grown in central and north-

ern Illinois and contiguous areas. Hard winter wheats have been grown there primarily because of their winter hardiness. They produce flour that is satisfactory for bread when the protein content is relatively high. They are not satisfactory either for bread or pastries—and hence constitute somewhat of a marketing problem—when the protein content is low, which is often the case. MICHIKOF and PURKOF, both hard red winter wheats from a cross between MICHIGAN AMBER and MALAKOF, (TURKEY), were produced to overcome this objection. They inherited most of the winter hardiness of MALAKOF, but, as would now be expected, contain no more protein than other varieties and like other hard winters are not satisfactory for pastry flours. BLACKHAWK, a cross between MINHARDI and FULTZ, is a soft variety that is very winter-hardy. It inherited most of the soft wheat qualities of FULTZ and is probably the most winter-hardy of any variety of soft red winter wheat grown by farmers. It was grown on about 72,000 acres in 1949, mostly in southern Wisconsin and northwestern Ohio, and is currently being recommended for northern Illinois. Its rather tall, weak straw lessens its popularity.

SALINE, a soft red winter of good soft wheat quality from a GLADDEN × ILLINOIS No. 2. cross, offers considerable promise for central and southern Illinois.

BUTLER and SENECA are new promising varieties for Ohio. BUTLER is from a (PORTAGE × FULCASTER) × TRUMBULL cross. It is believed to be an improvement over THORNE, especially with respect to test weight and resistance to scab. SENECA came from the same cross as THORNE. It has slightly stiffer straw and is characterized by a definitely higher test weight. It has outyielded THORNE in extensive tests in Ohio.

NURED, a soft red winter wheat, was distributed in New York primarily for feed because of relatively high yields and somewhat higher protein and vitamin B_1 content. It is no longer an important variety in New York or elsewhere. VALPRIZE, also distributed in New York, has been all but replaced by higher-yielding varieties. Farmers have objected to it because of a tendency for the heads to be broken by the reel of the combine (Love and Craig, 1946). The variety most recently produced by the New York Station is GENESEE, which was distributed to farmers in 1951. It originated from a cross between HONOR ^{2} × FORWARD × YORKWIN. In fairly extensive recent comparisons it has outyielded all other commercial varieties in New York, has been unexcelled for pastry qualities, has short stiff straw, and is resistant to most races of loose smut prevalent in New York.

The new varieties distributed in very recent years by the South Carolina and North Carolina Stations and the Coker's Pedigreed Seed Company promise much improvement in varieties of wheat for the south-

eastern United States. Derived in most cases from crosses involving the South American varieties FRONDOSO or FRONTEIRA, all are resistant to leaf rust and several to stem rust. Of special interest is their relatively high protein content combined with high yields due possibly to their resistance to leaf rust. ATLAS 50 and ATLAS 66, which were distributed in 1948, are proving to be very popular in North and South Carolina.

Of the remaining varieties of hybrid origin that have been in the hands of farmers long enough to judge their acceptability, PURDUE No. 1 soon disappeared because of susceptibility to mosaic and loose smut.

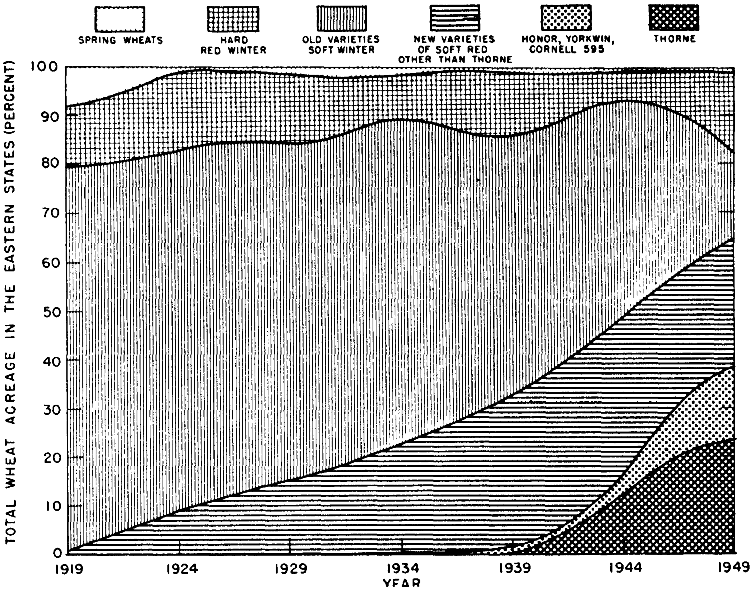

FIG. 21. Changes in important varieties of wheat in the eastern states.

BALDROCK was grown on only about 10,000 acres in 1949, and its acreage has been steadily declining since 1939, owing, no doubt, to competition with newer and better varieties.

The more important changes in varieties in the Eastern States from 1919 to 1949 are shown in Fig. 21. Because of the large number of varieties the changes are shown by groups: (1) all spring wheats; (2) all hard red winter varieties; (3) all old varieties of soft winter, that is, all that were grown before 1900; (4) new varieties of soft red winter wheat except THORNE; (5) THORNE; and (6) new varieties of soft white winter wheat. Perhaps the most interesting changes shown here are the rapid

increase of THORNE and of the new white varieties, YORKWIN and CORNELL 595.

c. Relative Yields and Increased Production. The more important varieties when the first varietal survey was made in 1919 were FULTZ, FULCASTER, MEDITERRANEAN, POOLE, RED MAY, RED WAVE, CURRELL, and LEAP. Excepting RED WAVE and LEAP, these had all been grown on farms previous to 1900. FULHIO and TRUMBULL were the first improved varieties produced by experiment stations to be widely grown. These were followed in turn by THORNE, YORKWIN, CLARKAN, FAIRFIELD, VIGO, and REDHART, each grown on 500,000 acres or more in 1949. Comparative tests for yield and other characteristics of varieties have been reported by Down *et al.* (1928), Bledsoe (1932), Down and Brown (1932), Brown and Down (1937), Etheridge and Helm (1938), Dungan *et al.* (1939), Kuykendall (1939), Middleton *et al.* (1940), Middleton and Hebert (1949), Cutler (1942), Bonnett *et al.* (1945), Love and Craig (1946), Caldwell and Compton (1947), Snell *et al.* (1948), Washko (1948), McMurray (1951), Lamb (1949), Gore *et al.* (1949), Poehlman (1949), Shulkcum *et al.* (1950), Josephson and Reid (1951), Pendleton *et al.* (1952), and Jensen (1951). Bayles and Taylor (1938–1950) have reported data for the Uniform Eastern Soft Wheat Nursery each year from 1938 to 1950, inclusive, and Taylor and Bayles (1942–1950) likewise for the Uniform Southern Wheat Nursery each year from 1942 to 1950, inclusive.

An estimate of the gains in yield is even more difficult than for other sections of the United States. The area is relatively nonhomogeneous, and the factors that determine varietal distribution and relative performance vary greatly from one section to another. Diseases are relatively unimportant in New York and Michigan but usually are determining factors along the southern fringe of the wheat belt and on the coastal plains and Piedmont areas from Georgia to Virginia. Relative winter hardiness largely determines the choice of varieties in Iowa and in central and northern Illinois, whereas nonhardy facultative types usually are the best for many sections of the southern and southeastern United States. The varying conditions limit the number of comparative tests, and hence there are not sufficient data suitable for estimating gains achieved on farms. Finally, many of the data that have been accumulated have not been published. Nevertheless, it is believed that enough data are available to provide some general ideas of the improvements that have been made.

The improvements can best be rated by considering each more or less homogeneous sections separately. One such section comprises Ohio, Indiana, Pennsylvania, New Jersey, northern Maryland, and southern

Illinois, roughly the area in which THORNE was grown in 1949. Table XVIII shows the number of comparative yield tests for various pairs of varieties in this area and the average yields of each variety of each pair. The varieties are arranged roughly from left to right in the order in which they were first grown in farmers' fields. So far as possible, each variety is paired with FULCASTER or FULTZ. Newer varieties that were not grown in comparison with FULCASTER and FULTZ are paired with other new ones that preceded them. These yield tests include field plots and replicated multiple-row nursery plots but not single-row nursery plots.

It will be noted that with no important exceptions FULCASTER and FULTZ produced on the average as well as the varieties that preceded them. FULCASTER outyielded FULTZ by 0.8 bushel in 192 comparative trials. FULTZ has generally been the more popular variety, however, probably because it is beardless and generally lodges less than FULCASTER.

It is doubtful if FULCASTER or FULTZ is more productive than the best of the other old varieties considered here with the exception of RED MAY and MEDITERRANEAN. RED MAY was never an important variety in this area except in Indiana and in that state was grown less extensively than others. FULCASTER averaged 0.9 bushel more than MEDITERRANEAN, which like RED MAY has been more generally grown south of, or along, the southern fringe of the area here considered. It should be noted that before 1919 many varieties other than those considered here were grown extensively in this area and were included in experimental trials, found wanting, and discarded. In view of these facts, it seems reasonable to assume that FULCASTER and FULTZ added at least 1 bushel per acre to the area in which they were grown.

No increase can be credited to FULHIO, but TRUMBULL averaged 1.1 bushels more than FULCASTER in 89 trials and 0.8 bushel more than FULTZ in 212 trials. THORNE in 429 trials mostly in Ohio averaged 2.2 bushels more than TRUMBULL, and FAIRFIELD in 147 trials averaged 2.6 bushels more than TRUMBULL. VIGO yielded about the same as FAIRFIELD. The comparisons of FAIRFIELD and VIGO with TRUMBULL or indirectly with THORNE must be accepted with considerable caution for various reasons stated above, and also because FAIRFIELD, VIGO, and TRUMBULL or THORNE are probably best adapted to somewhat different sections within this fairly large area. THORNE has outyielded FAIRFIELD in Ohio, whereas the reverse is true in Indiana. Yields in experimental plots have averaged about 10 bushels above the average production on farms. An estimated increase in yields on farms of 1.5 bushels per acre for THORNE, FAIRFIELD, and VIGO over TRUMBULL, or 2.5 bushels over the varieties grown before 1900, would seem reasonable. For the 1949 acreage of THORNE, FAIR-

TABLE XVIII

Comparative Yields (bushel per acre) of Important Varieties in the Ohio, Indiana, Pennsylvania, New Jersey, Northern Maryland, and Southern Illinois Area *

Number of trials	RED MAY	MEDITERRANEAN	MEDITERRANEAN	CURRELL	POOLE	POOLE	RED WAVE	FULCASTER	FULTZ	FULHIO	TRUMBULL	TRUMBULL	THORNE	FAIRFIELD	VIGO
43	27.0							29.5							
36		27.9						28.8							
59			26.0						25.9						
98				24.4				24.2							
140					30.5			30.7							
191						31.3			31.2						
40							29.1	29.5							
33								25.9		24.5					
89								32.4			33.5				
212									29.5			30.3			
429												32.1	34.3		
147												31.8		34.4	
35														33.7	34.3
192								30.5	29.7						

* The original data from which the data of this table were compiled and much of those in the text have been published and are referred to in the text or they have been secured in cooperation with the State Agricultural Experiment Stations of Illinois, Indiana, Michigan, New Jersey, New York, Ohio, Pennsylvania, West Virginia, and Wisconsin.

FIELD, and VIGO this would mean an increase in production of about 11,500,000 bushels, or about 9,000,000 bushels for the average acreage of the past ten years. Lamb (1948) has estimated that the potential production of wheat on Ohio farms has been increased by about 6,000,000 bushels by the Ohio wheat improvement program, as compared with what would be produced by growing FULTZ, FULCASTER, and POOLE.

A considerable number of new varieties have been distributed recently in Missouri, Iowa, and Illinois. The more important are PAWNEE, BRILL, and IOWIN, hard wheats; and CLARKAN, ROYAL, PRAIRIE, and NEWCASTER, soft wheats. The number of comparative trials for which the records are available is not sufficient to provide a sound basis for evaluating their contributions. Pendleton *et al.* (1952) point out that, whereas TURKEY was the best variety for Illinois early in the century, its yield at Urbana now is 3 bushels less than the average of all varieties in yield tests and that the three varieties now recommended for Illinois (which includes PAWNEE) "are outyielding TURKEY by 9 bushels per acre." Also of much significance in relation to quality characteristics and marketing is the fact that varieties of soft wheat now available equal or exceed the hard wheats in average yield. Poehlman (1949) refers to PAWNEE as "one of the highest-yielding varieties of winter wheat" and also to "its popularity among farmers in west and central Missouri."

PAWNEE and CLARKAN were each grown on more than ten times as many acres as any other variety in Missouri in 1949. PAWNEE was grown on twice as many acres as any other variety in Illinois in 1949 and on five times as many acres as any other variety in Iowa. There scarcely can be any doubt that larger per acre yields as compared with other varieties is the principal reason for their popularity. From the meager published experimental data available for the area the estimated gain in yield for PAWNEE is 3 bushels and for CLARKAN 1½ bushels per acre. This means an increased production of about 7,000,000 bushels for 1949 or 5,000,000 bushels for the ten-year average acreage.

Available data comparing yields of YORKWIN and CORNELL 595 with other varieties in New York and Michigan are not sufficient for a statistical evaluation of the gains resulting from their production. Love and Craig (1946), in commenting on the increase in the average yield of wheat in New York from about 15.0 bushels per acre before 1895 to the current yield of about 25.0 bushels, state that "no doubt the low yields for the earlier years are due to several factors, the most important being that the varieties then used were not well adapted." Some of the increase they attribute to the varieties HONOR and JR. NO. 6 (a synonym of GOLDCOIN), which were first grown by farmers in 1920, and some to YORKWIN, which was distributed to farmers in 1935. The increase due

to the later variety they say may "be fairly assumed" to be "one or two bushels per acre." This would appear to be a very conservative estimate in view of the results of an eight-year comparison reported by them in which YORKWIN averaged 6.2 bushels per acre more than JR. No. 6 and 4.8 bushels more than HONOR. In this same test CORNELL 595 outyielded YORKWIN by 5.2 bushels, JR. No. 6 by 11.4 bushels per acre, and HONOR by 10.0 bushels per acre. Later data reported by Jensen (1951) indicate a gain for CORNELL 595 of 1.9 bushels over YORKWIN as an average of fifty-eight tests conducted from 1943 to 1950. Data reported by Bayles and Taylor (1938-1950) indicate an average gain of 4.6 bushels for YORKWIN over AMERICAN BANNER (synonym for DAWSON) for a period of ten years at Ithaca, New York, and of 2.0 bushels per acre for ten station years in Michigan.

If improved varieties is the most important factor responsible for increased yields in New York, as stated by Love and Craig (1946), it would seem reasonable to credit YORKWIN and CORNELL 595 with average increases of somewhere between 3 and 5 bushels per acre. An average of 4 bushels per acre would mean an increased production of 5,800,000 bushels on the 1949 acreage or about 4,000,000 for the ten-year average acreage.

Along the coastal plain and in the Piedmont areas of Georgia, South Carolina, North Carolina, and Virginia, REDHART, SANFORD, and HARDIRED have largely replaced the old varieties PURPLESTRAW, RED MAY, and FULCASTER. The total acreage of the new varieties in 1949, grown mostly in these states, was about 879,000 acres. The variety now grown as REDHART consists largely of REDHART 3 and REDHART 5, produced by the Coker's Pedigreed Seed Co., of Hartsville, South Carolina, from a cross between REDHART 1 (a selection from FLINT) and a variety known as GOLDEN CHAFF. In extensive tests throughout the South, REDHART 3 and REDHART 5 have given essentially the same average yields as PURPLESTRAW. They are considered superior varieties, however, for the Coastal Plains and lower Piedmont areas of North Carolina and South Carolina, where they are grown partly because of their earlier maturity. SANFORD has averaged about 4 bushels per acre, and HARDIRED about 6 bushels per acre, more than PURPLESTRAW. They were grown on about 275,000 acres in 1949, SANFORD principally in Georgia and HARDIRED principally in North and South Carolina. Probably the total production is about 1,000,000 bushels above what it would be with the older varieties.

A number of additional improved varieties have been distributed in various Eastern States for which no attempt has been made to evaluate their contribution to increased yields. Acreages of each individual variety are relatively small, but the total was about 2,000,000 acres in 1949.

They probably yield on the average at least a bushel per acre more than the varieties generally grown at the beginning of the century.

Altogether, these estimated increases amount to about 21,000,000 bushels per year for the Eastern States owing to improved varieties as compared with those grown fifty years ago.

d. Quality. Quality of varieties grown in the Eastern States has received more or less attention since before the beginning of the century. For many years, varieties were evaluated entirely or almost entirely in relation to their use for bread. In recent years their possible uses both for bread and pastries have been considered. Extensive studies relating to quality have been conducted especially during the last ten or fifteen years. Results of these studies have been reported by Bayfield *et al.* (1937, 1938), Morris *et al.* (1939–1947), and by Bode *et al.* (1948–1950). It has not been possible to summarize these data in this paper.

6. *Recapitulation*

Two hundred and eighty-four new varieties of wheat have been developed and grown on farms of the United States since 1900. Eighty-eight originated as plant or head selections from old varieties, 127, including 6 natural hybrids, originated from hybridization of 2 or more varieties, 55 originated as introductions from other countries, and the origin of 14 is undetermined. Of the hybrids, 21 were developed by back-crossing and released to farmers during the past twenty years.

There has been a marked shift in emphasis since 1900 from the use of introductions and selections to hybridization as a method of improving wheat. During the first twenty years (1901–1920), for example, about 31 per cent of the new varieties had been produced in this country by selection from older varieties, and 22 per cent were of hybrid origin. Most of the introductions were of old varieties or recent selections from old varieties made in the country from which they had been introduced. On the other hand, more than 79 per cent of the varieties released to farmers during the past twenty years (1931–1950) were of hybrid origin, about 18 per cent were selections, and about 3 per cent were introductions. All the introductions during this period were spring varieties produced by Canadian workers by hybridization.

Farmers, seedsmen, and other commercial interests are primarily responsible for the distribution of 79 of the 284 varieties and state and Federal experiment stations for 197. For 8 the record is not clear. Probably most of the latter originated as selections by farmers or seedsmen. In a few cases they may be old varieties masquerading under new names. Checking and comparing allegedly new varieties with the old has in recent years practically eliminated this latter practice.

A total of 199 varieties were reported as growing on farms in 1949. Of these, 154 were new varieties developed since 1900. They accounted for 91.8 per cent of the wheat acreage in 1949. Ninety-eight of the 199 occupied 50,000 acreas or more each, and 19 of them were grown on 1,000,000 acres or more each. This compares with 46 grown on 50,000 acres or more, and 12 grown on 1,000,000 acres or more, each in 1919. The acreage of wheat in 1919 was, however, only about 87 per cent as great as in 1949. The greatest acreages for single varieties in 1919 were 21,588,000 acres for TURKEY and 11,825,000 acres for MARQUIS. Corresponding figures for 1949 are 11,121,000 acres for PAWNEE and 5,932,000 acres for COMANCHE. In 1919 TURKEY was grown on 29.6 per cent of the total wheat acreage; in 1949 PAWNEE was grown on only 13.1 per cent of the wheat acreage. In other words, a larger number of varieties with fewer acres of each is now the rule, as would be expected with a greater diversity of germ plasm and better adaptation to local conditions.

The total estimated annual increase in production due to new improved varieties, based on a ten-year average acreage in each region equal to that in 1941–1950, is as follows:

Hard red spring and durum	101,611,000 bu.
Hard red winter in the Great Plains	85,412,000 bu.
Western States	23,769,000 bu.
Eastern States	21,000,000 bu.
Total:	231,792,000 bu.

This estimate does not take into account the possible contributions of many new varieties grown on only a few thousand acres nor of the increase in acreage of many new varieties since 1949. The latter is quite important. A survey of wheat varieties in Kansas in 1952 by the Kansas State Board of Agriculture and the United States Department of Agriculture, for example, indicates a considerable increase in the acreage of PAWNEE, WICHITA, and other new varieties since 1949. The results of a survey of the 1951 crop in the Pacific Northwest, reported by the Pacific Northwest Crop Improvement Association, indicates a considerable increase in the acreage of the high-yielding variety ELGIN. The performance of the new varieties ELMAR and BREVOR and the demand for seed indicates that these varieties accounted for a considerable part of the 1952 crop in the Pacific Northwest. Informal reports suggest that VIGO may now be grown on more than twice the acreage reported in 1949. REDHART and HARDIRED are known to have been replaced to a considerable extent by the newer and more productive varieties including ATLAS 50, ATLAS 66, CHANCELLOR, COASTAL, and COKER 47-27. Probably more than one-half of the wheat acreage in North and South Carolina is now

devoted to ATLAS 50 and ATLAS 66. CHANCELLOR has replaced a considerable part of the acreage of SANFORD in Georgia.

Since the actual amount of these increases in acreage is not known, no attempt has been made to include increases due to them in the over-all estimates. It would be surprising, however, if they are not sufficient to bring the total estimated increase to 235,000,000 bushels or more per year, or an increase of about 40 per cent above the average production for the ten years ending in 1900. In all areas there has been also a definite, and in some cases a material, improvement in quality. Losses from shattering and lodging have been reduced, and production has been stabilized by reducing losses from winterkilling, disease, and insect pests.

It seems desirable to repeat that this estimate depends on several assumptions which cannot be verified and which vary somewhat for each wheat-growing region, as pointed out in the discussion for each region. Also, as pointed out for some of the wheat-growing areas, that part of the gain in production brought about by better adaptation to climatic hazards may be regarded as permanent, since climate changes very slowly. Another part is dependent on whether disease and insect pests are kept under control as effectively as has been done in recent years. This is an important qualification, since it is well established that new races may be produced in nature or those of minor importance may and do become widely distributed and eliminate some of the advances that have been made if research does not keep pace with needs. However, there seem to be no sound reasons why this cannot be done.

7. *Varieties for the Future*

A natural question is whether even better varieties may be produced in the future. Paradoxical though it may seem, the prospects are even brighter than they were fifty years ago. Never in the history of wheat breeding have such large gains in average yield for comparable periods of years been recorded as those for ELGIN in the Pacific Northwest; for PAWNEE, COMANCHE, and others in the southern Great Plains; for ATLAS 50 and ATLAS 66 in the southeastern United States; and for several new varieties still in the yield testing stage in various parts of the United States. These latter, it is true, are preliminary and for relatively short periods of years. Some of the promising varieties will, no doubt, be found wanting, but, contrary to this, some will be better than any we now have if past experience is a reasonably dependable guide.

There is abundant evidence to prove the superiority of early-maturing varieties for the southern Great Plains, but the degree of earliness that is most desirable for smaller segments of the Great Plains is not yet known. Acquiring this information would almost certainly lead to fur-

ther improvements. The use of very early-maturing varieties of winter wheat is limited to the southern portion of the Great Plains because no one has yet succeeded in producing early varieties that are sufficiently winter-hardy for the more northern portion. But enough progress has been made to be reasonably certain that a partial solution, at least, is possible. So far it has not been possible to transfer the winter hardiness of winter rye or of the agropyron grasses to wheat. Although the difficulties are great, it should be noted that our knowledge of the genetic constitution and physiology of wheat and wheat relatives is very limited.

Large acreages are still occupied by varieties that grow too tall and lodge too easily. Experience in the Pacific Northwest and elsewhere suggests not only that lodging may be reduced but also that yields may be increased by producing varieties with shorter straw. Material progress has been made in breeding varieties that are resistant to wheat rusts, as noted above, but for no area in which they prevail has there been produced a variety that is resistant to all races and that is satisfactory in other respects. Hessian fly-resistant varieties have been produced for only a small part of the areas where this insect is a recurring menace. Practically nothing has been done to produce varieties that are resistant to greenbug or aphids, to wheat-stem worms, chinch bugs, jointworm, mildew, septoria, and a host of other diseases and insects that attack wheat. In about the same category is breeding wheat for resistance to drought and high temperature except for what may have been achieved by comparative yield tests in dry areas. No one, of course, expects varieties that will grow without water or will not be injured by excessively high temperatures. On the other hand, it can scarcely be doubted that varieties differ in these respects and that precise knowledge of these differences would permit a far greater use of them. The surface of many of these problems has scarcely been scratched. The reason is not that wheat breeders and agronomists have been unaware of them, but simply and clearly because of lack of time, trained personnel, and adequate equipment to attack them.

V. Improvements in Methods of Breeding Wheat

A most important reason for the great advances in the improvement of varieties of wheat during the past fifty years is the better and more effective methods and techniques that have been developed. These are largely the result of a better understanding of genetics and of the factors that govern the adaptation of varieties, especially the role of weather, disease, and insect pests; of more complete knowledge of these pests, especially with reference to physiologic races; and of the develop-

ment of special techniques for determining varietal resistance to weather hazards and pests of various kinds. Methods for measuring quality have been greatly improved and simplified. More complete knowledge of the genetic constitution of the wheat plant has greatly facilitated the choice of parental varieties, the selection of progenics, and breeding procedures.

1. *Early Methods of Breeding*

Continuous mass selection of the largest and best-appearing heads of the heaviest and plumpest grain separated by wind or sieves was generally recommended and used at the turn of the century, as it had been since the time of the Romans and even before. Publication of *The Origin of Species* by Darwin in 1859 provided a theory that greatly stimulated the belief that important improvements could be achieved by continuous selection.

Le Couteur and Shirreff initiated the practice of selecting single heads and plants early in the nineteenth century. Shirreff emphasized the importance of the initial selection and believed that little or nothing was gained by later selection. Hallett (1861) proposed a "pedigree method" which consisted essentially of selecting the largest grain from the longest and largest head from the best plant each year and continuing this year after year. Four years of selection doubled the length of the head, trebled the number of grains per head, and increased the tillering fivefold. He believed that yields per acre were also greatly increased. Some breeders followed the method developed by Shirreff, but Hallett's philosophy predominated until the close of the century and did not disappear until the end of the first decade or later of the present century.

Willet M. Hays of the Minnesota Station in about 1895 applied to wheat breeding the concept of the progeny test to determine the relative superiority of selected strains. He developed the centgener method of planting for spacing the plants and thereby facilitated the selection of the best individual plants each year. The method was widely adopted throughout the United States.

This, in brief, was the prevailing theory and practice until the publication of Johannsen's pure-line theory in 1901. This publication plus accumulated general experience, including carefully controlled experimental trials at a number of experiment stations, turned the attention of wheat breeders to the selection of pure lines and the determination of their relative value. Most of the improved varieties of the first three decades of the twentieth century were the product of this method. They include such varieties as KANRED, NEBRASKA NO. 60, CHEYENNE, IOBRED,

IOWIN, KARMONT, MONTANA NO. 36, FULHIO, TRUMBULL, NITTANY, GASTA, MINDUM, NODAK, KOTO, PROGRESS, and others.

Hybridization, it is true, was practiced by a number of breeders before 1900, notably Farrer in Australia; Saunders in Canada; and Blount, Pringle, Jones, and Spillman in the United States, but it received relatively little attention. The principal purpose of hybridization was to induce variation or to "break the type" and thereby afford greater opportunity for selection. Consequently, parents were chosen more or less at random. A few breeders had clearly in mind the possibility of combining in a single variety the desirable characteristics of two or more. Saunders recognized the need for early maturity when he crossed Hard Red CALCUTTA with RED FIFE to produce MARQUIS, and Spillman set out to combine resistance to shattering and winter hardiness in the Washington hybrids. Not until several years after the rediscovery of Mendel's laws, however, was there general recognition of the value of hybridization and the need for a careful choice of parents based on their known characteristics.

A development traceable directly to a better understanding of genetics is the backcrossing technique, first proposed by Harlan and Pope (1922) and used especially by Briggs (1938) and associates in California. It has also been used extensively in the breeding of rust-resistant durums but sparingly elsewhere. Percival (1921) and Clark (1936) reviewed the methods generally used during the last century and in the early part of the 20th century.

2. *Objectives in Breeding*

Another development of first importance is the clearly defined objectives of most modern wheat-breeding programs. Early efforts were directed mostly to increasing yields but without any clear concept of what determined yield. It was assumed that varieties differed in "yielding capacity," as, without doubt, they do and also that "yielding capacity" is synonomous with actual yield, which usually is not the case. Plant breeding often was regarded as an art; this implied that breeders acquired a special skill that enabled them to choose heads or plants that would produce superior yields. Undoubtedly, there is some truth in most of these assumptions, but there is also a great deal of error. This concept again was not accepted universally. Carleton (1900, p. 54), for example, stated that "yield after all is not a distinct quality in itself but is the combined result of a number of qualities acting independently and not thought of at all."

Much information as to yield factors is still lacking, but few probably will doubt that wheat breeders are on solid ground in breeding for re-

sistance to stem rust in spring wheat for the northern Great Plains, in breeding for appropriate degrees of winter hardiness in winter wheats, and in breeding for resistance to all diseases and insect pests and weather hazards so far as is feasible and for areas where they are known to be important. The important difference is not that the modern wheat breeder ignores yield, but that he uses what information he has more effectively in producing higher-yielding varieties. His efforts are more effective because it is much easier, less expensive, and less time-consuming to test selections for reaction to individual factors that affect yield than it is to determine relative yields. If a modern wheat breeder uses the term "yielding capacity" at all, he means yielding capacity under a specified set of environmental conditions.

A closely related achievement also of importance is the relatively more precise knowledge of the kind of wheat needed for each wheat-growing area. The wheat breeder has learned, mostly the hard way, that nowhere in the United States are varieties wanted that mature as late as those of northern Europe or as early as those grown in India: that varieties even earlier than TURKEY are needed for the southern Great Plains; that in much of the northern Great Plains varieties of spring wheat susceptible to rust have little chance of successful competition with similar varieties that are resistant to rust; that short stiff-strawed varieties are needed for the Pacific Northwest. There is now a clearer concept of the degree of winter hardiness needed for each principal wheat-growing area and also general recognition of the fact that winter hardiness in one area does not necessarily mean winter hardiness elsewhere. If it is necessary, as seems probable, to accept a compromise between extremes of winter hardiness and of early maturity in hard winter wheat, current knowledge as to the needs with respect to each should make it easier to attain a suitable compromise.

3. *Resistance to Disease, Insect, and Weather Hazards*

Certainly among the most important advances in techniques are those for testing the resistance or tolerance of varieties and selections to specific disease, insect, and weather hazards. Wheat breeders no longer wait for natural epidemics but produce what is needed where and when it is wanted. This method, first proposed by Bolley (1905) soon after 1900 for breeding varieties of flax resistant to wilt, has been all but universally adopted for other crops and diseases wherever feasible. Seed is inoculated with specific races of the bunt organism and seeded late to insure suitable temperatures for infection or, in the case of dwarf bunt, the seed is planted in infected soil. Plantings for leaf and stem rust resistance are provided with border or so-called spreader rows of a sus-

ceptible variety which, in turn, are artificially inoculated and watered with overhead sprinklers to provide suitable atmospheric humidity for the germination of the rust spores. Cherewick (1946) has recently described the methods used in Canada for establishing rust epidemics in experimental plots. Cartwright and LaHue (1944) have developed a technique for testing varieties and selections for resistance to Hessian fly by means of which 20,000 or more may be tested in a single season. Platt and Farstad (1946) have described a method for insuring epidemics of sawfly that has proved most useful in breeding for resistance to this insect in Canada and the United States. It consists essentially of seeding short rows of the material to be tested on summer fallow and adjacent to infected stubble of the preceding crop. The rows are seeded at right angles to the stubble in order to insure like infestation of all rows, since infestation depends materially on the distance the flies must migrate. An important feature, emphasized by Platt and Farstad in the interests of economy of labor, is to estimate infestation rather than make actual counts. The latter is very laborious and time-consuming, and estimates were found by them to be sufficiently accurate for most purposes. Similar methods incidentally are widely used and with satisfactory results in determining relative resistance to rust, bunt, Hessian fly, winterkilling, lodging, shattering, and other diseases and hazards.

The development of greenhouse techniques not only for determining resistance to diseases and insects but also for growing two or more generations per year has been most important. Resistance of selected lines can be determined before the time for seeding in the field the following spring. The F_2 or segregating generation of a cross is reached a year earlier by growing the F_1 generation in the greenhouse. Closely related is the practice of seeding a crop in the field in Arizona, southern California, or Mexico, and shipping the product back to the northern United States for planting the following spring. Relatively rapid increases in the quantity of seed of promising varieties have been made in this way.

The relative winter hardiness of new varieties or selections for Central and Southern States is frequently determined by seeding them in Northern States where partial but not complete killing may be expected. Artificial freezing tests have been used although not extensively, largely because equipment is expensive and not readily available. The use of winter-hardiness nurseries and others for similar purposes has been greatly facilitated by the co-ordinated co-operative programs previously described. Relative shattering and lodging are now easily, simply, and inexpensively determined by permitting border rows to stand for several weeks after the normal harvesting date and estimating the loss due to either or both.

Unfortunately, no simple or even dependable methods for testing relative drought resistance have been developed other than relative yields in a dry area for a long period of years.

4. *Testing for Comparative Yields*

Field plots of various sizes seeded with an ordinary grain drill were used for determining relative yields of varieties long before the end of the nineteenth century. Usually there were single plots only of each variety, although occasionally duplicate, triplicate, or even quintuplicate seedings were made. One-tenth acre was a common size plot. It was recognized early that soil variation often seriously vitiated experimental results; consequently, much attention was devoted in the early years of the century to the selection of uniform land for experimental fields, uniform preparation of the land, improvement in uniformity by drainage, etc., and in extreme cases to the relocation of experimental fields in order to have reasonably uniform land. The use of replicated plots in the United States has been almost universal since about 1915, largely as a result of the application of statistical methods to field experiments. In recent years the combine has been used to harvest experimental field plots with a material saving in labor.

Probably the most important single advance in methods of comparing yields was effected by the substitution of rod-row plots for centgeners. Rod-row plots were first extensively used by Norton (1907). The universal adoption of this and similar methods has resulted in a saving of labor, and hence in an opportunity to compare more selections, which it is difficult for those who have not used a centgener machine to appreciate. There can be little doubt also that modern rod-row tests are more accurate than those made by the centgener method, although there appear to be no data to prove it. An important contribution to the accuracy of rod-row tests was the demonstration by Kiesselbach (1918) at the Nebraska Station of border effect, and as a consequence the general adoption of multiple-row plots.

Kezer (1906) correctly believed that he had made an important contribution when by substituting a movable for a fixed frame, he and five men were able to plant the equivalent of 275 centgeners per day as compared with 80 with the machine previously used. But contrast this with 100 rod-rows or 150 head rows per hour per man by modern plant-breeding crews. Many yield nurseries are now seeded with drills powered by small tractors, harvested and bound into bundles mechanically, and threshed with improved threshing machines having probably twice the capacity of those available in 1900. Magee (1951), for example, has

estimated that three men with a tractor-mounted drill used by him "can seed more than 5 men using hand seeders."

One thousand centgeners was a big nursery around 1900. It is not unusual for a modern wheat-breeding and yield nursery to comprise 10,000 or even 20,000 rows. The improvement, it should be noted, is due not only to better techniques of planting, harvesting, threshing, etc., but also to changes in specific objectives, as noted above, which greatly reduce the time devoted to each item. For example, many selections are now discarded without harvesting with perhaps no more than a record of their defects. With the centgener method and the philosophy accompanying its use, detailed notes were recorded often for each individual plant in each centgener.

5. *Techniques for Measuring Quality*

Striking improvements in methods of measuring or comparing quality have been made since Saunders used the chewing test to determine the quality of MARQUIS. At least four distinct categories must be recognized: milling quality; quality for bread; quality for cake, cookies, crackers, and similar products collectively called pastries; and in the case of durum wheat, quality for macaroni.

a. Milling Quality. A good milling variety in the eyes of the miller is one that mills easily and produces a high yield of flour, especially of patent flour. Improvements in techniques for determining or measuring milling quality have been few. They have consisted mostly of standardization and refinements in the operation of experimental mills, and there have been some improvements in the mills themselves, especially adjustments to enable satisfactory tests to be made on small samples. Recent studies indicate that it may be possible to relate poor milling properties to definite physical or chemical characteristics of the grain and thus facilitate the identification of poor milling varieties.

b. Quality for Bread. Perhaps the most important advances in techniques relating to measuring quality are those for quality of bread. The history of the subject is surprisingly confusing in view of the rather clear picture that has emerged in recent years. The literature is voluminous, and only the barest outline can be presented here. Larmour (1940) has given an informative account of much of the research in the field up to about 1940 as it relates to a comparison of hard red spring and winter wheat.

Quality of undamaged or normal wheat and flour for bread has long been known to depend on quantity and quality of protein. Protein content is easily determined, but until recent years there was no adequate test for protein quality. The latter was at best inaccurately estimated

from the baked loaf and then only when interpreted in terms of the quantity of protein in the flour; that is, if differences in the quality of bread could not be explained by differences in protein content, they were automatically attributed to protein quality. Interpretation was usually difficult and inaccurate, and especially so if the protein contents of the varieties being compared were different.

This difficulty stemmed principally from the general experience, as shown by Thomas (1917), Coleman *et al.* (1927), and Shollenberger [cited by Larmour, (1940)], that the relation between protein content and loaf volume by the methods then used is nonlinear. Flours with a medium protein content would generally produce better bread than those with a low protein content but would also usually produce as good bread as flours with very high protein content. Yet it was known that high protein flours used in blends with low protein flours would improve the latter in proportion to protein content.

This paradox was cleared up by a long series of investigations, including those by Larmour and MacLeod (1929), Geddes and Larmour (1933), Larmour and Brockington (1933), Ofelt and Larmour (1940), Larmour (1940), and especially Finney and Barmore (1944, 1945, 1948). Briefly, it was found that the baking test formulas and procedures then used were such that the potential value of high protein flour was not expressed. As a corollary, it was found that when proper formulas and techniques are used, the relation between protein content and loaf volume is perfectly or almost perfectly linear, at least within the range ordinarily found.

Another important discovery was that the slope of the regression line is a varietal characteristic and such that for a large number of varieties differing in protein quality, they fall into a fan-shaped pattern with relatively little difference between them at low protein levels and wide differences at high protein levels. This means that for the first time cereal chemists have an adequate and reasonably accurate measure of protein quality.

Very recently it has been found that exposure of the growing wheat to excessively high temperatures and relatively low humidities during the latter part of the fruiting period may deleteriously affect protein quality and distort the usual linear relation between protein content and loaf volume. Other environmental factors may require consideration but even so the bread-baking test is far superior to that of fifty years ago.

c. Pastry Quality. The fact, long suspected but not proved until recently that pastry quality depends more on the physical properties of the flour and on the characteristics of the protein than on the protein content, has been of great assistance in evaluating varieties for pastry

purposes. The most generally acceptable evaluation is by means of the cooky-baking test. Cake-baking tests are generally less useful because small differences are obscured, probably because flour constitutes less than half of the ingredients in a cake formula. Cooky-baking tests apparently were first proposed by Alexander (1933), first used for evaluating varieties by Fifield *et al.* (1936–1950), and since greatly improved by Finney and Yamazaki (1946) and Finney *et al.* (1950).

d. Bread-Baking Tests for Soft Wheat. At the beginning of the century and for many years thereafter, soft wheats for the Eastern States were evaluated by bread-baking tests. One reason was that soft wheats were then extensively used for bread and family flours. Another reason, probably not widely accepted, was the assumption that varieties of poor quality for bread were suitable for pastries and vice versa. This, as is now well known, is only partly true. Important here, especially in relation to future breeding, is the discovery that the suitability of certain varieties of soft wheat for bread or for pastries depends on their protein content, which is determined mostly by environment. If high in protein content, they may be used for bread, and if low in protein content, they may be used for cakes, cookies, crackers, and other pastry products. This is true, however, only for those varieties that yield flours having the necessary desirable physical properties.

e. Macaroni Quality. Macaroni tests for quality of durum varieties, the only tests available during the early years of the century, are especially time-consuming and like the bread-baking tests require considerable grain. Relative quality of durum varieties is now regularly determined by the disk test first proposed by Fifield *et al.* (1937). In this method, the wheat is milled to produce semolina in the usual way. Semolina dough is then pressed into disks one-fourth of an inch thick and with about the diameter of a silver dollar. Translucency and color, on which quality for macaroni depends, can be determined from them as easily and as accurately as from macaroni. In terms of labor and time, the disk test is seven or eight times as efficient as the macaroni test. Macaroni is still sometimes made for final evaluations of promising new varieties but otherwise is seldom needed.

f. Ancillary Quality Tests. Baking tests whether of bread or cookies are time-consuming and relatively expensive. They also require more flour than is usually available in early-generation selections from a cross. Consequently, there has been an urgent need for simple chemical or physical tests that require less time and less flour. This need has in part been supplied by various tests including the (1) viscosity test, (2) dough-ball, Pelshenke, or fermentation time test, (3) pearling test, (4) mixogram curves, (5) water-absorption test, (6) the sedimentation test, and

others. None of these can be completely substituted for baking tests, but each provides a certain kind of information that is most useful in evaluating quality and especially so in early generations, since each test requires only a small quantity of grain. Finney and Yamazaki (1953) have recently developed an alkaline viscosity test, and Yamazaki (1953) has developed an alkaline water-retention capacity test for soft wheat flours that correlates very highly with the cooky test. Micro-milling and micro-baking test procedures, developed by Finney and Yamazaki (1946) and Finney *et al.* (1950), are now available that require only a small quantity of grain and hence are useful for testing quality in early generations.

VI. Control of Diseases

Little was known about the nature of wheat diseases or how to control them before the beginning of the twentieth century. Loose smut and stinking smut or bunt were widespread, and the latter especially threatened to become a limiting factor in wheat production in many areas. Control methods known at that time were inconvenient or ineffective or both and were not generally used until severe losses had occurred. Both stem and leaf rust were recognized as important diseases in many sections. Other diseases were present, but most of them had not been identified and fully described as to symptoms, causal organisms, and manner of spread.

1. *Stem Rust*

a. History and Distribution. Some important facts regarding stem rust had been established before the twentieth century, such as the general characteristics of the causal organism, the role of the barberry as an alternate host, and the fact that the variety of stem rust that attacks oats, for example, does not attack wheat.

Laws to enforce the eradication of the barberry were passed in Connecticut, Rhode Island, and Massachusetts between 1726 and 1766, long before the relationship between barberry bushes and stem rust infection was clearly established. The existence of physiologic races that attack some varieties of wheat but not others was not known, nor had the role of wind-blown spores in producing stem rust epidemics been discovered. Carleton (1900) and others had recognized differences in susceptibility of varieties to stem rust, but resistant varieties, as we know them today, were not available.

b. Development of Resistant Varieties. The discovery of the outstanding resistance to stem rust in IUMILLO durum wheat and in YAROSLAV emmer marked the beginning of the first successful attempts to breed

resistant varieties. So far as the writers are aware, the details of this discovery have never been published. The first significant observations regarding the rust resistance of these varieties were made at the South Dakota Agricultural Experiment Station at Brookings in 1902, when Mr. John S. Cole, then in charge of the cereal-breeding plots, reported in part as follows: *

"Rust damage to common spring wheat was so great that no comparisons could be made that were of any value. . . . Durum wheats from Spain, Italy, and Bulgaria . . . show but little promise. One, however, NO. 1736, a wheat of peculiar type from Italy, appears to be almost perfectly resistant to black rust and promises to yield well." NO. 1736 is IUMILLO, which later provided most of the genes for the resistance of THATCHER to stem rust. Cole also stated: "Results with emmers were very striking, especially in the matter of rust resistance. Four varieties were found to be highly resistant to rust and yielded about 40 bushels per acre, whereas the yield of other varieties grown under the same conditions, but which rusted severely, went as low as 4 bushels." Among these four resistant varieties was YAROSLAV emmer, which McFadden later crossed with MARQUIS in producing HOPE and H-44 and from which most of the genes for resistance in common spring wheats other than THATCHER have been derived.

Cole's observations were verified during the famous stem rust epidemic of 1904 and again in 1905. By 1904, the varieties mentioned by Cole were being grown at other stations where observations regarding their rust resistance served to call attention to the possibilities of using them in breeding programs. For further details, the reader is referred to Ausemus' (1943) excellent review of breeding for resistance to stem rust and other diseases in wheat and other small grains.

c. *Discovery of Physiologic Races.* Another contribution of basic importance regarding the rust fungus was the discovery in 1917 of the existence of physiologic races that attack different varieties of wheat. This outstanding contribution was made by Stakman and his associates at the Minnesota Experiment Station (Stakman and Piemeisel, 1917; Levine and Stakman, 1918).

d. *Barberry Eradication.* The disastrous stem rust epidemics in 1904 and 1916 were chiefly responsible for the region-wide barberry eradication laws passed by North Dakota in 1917; by South Dakota, Minnesota, Iowa, Nebraska, Colorado and Michigan in 1918; and later by Montana,

* Report of the cooperator's work on cereals at the South Dakota Agricultural Experiment Station during the season of 1902. Nov. 7, 1902. (Unpublished.) Filed with the Division of Cereal Crops and Diseases, Bureau of Plant Industry, Soils, and Agricultural Engineering.

Wyoming, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, Virginia, West Virginia, Missouri, and Washington. By 1950 about 340,000,000 bushes had been destroyed and about four-fifths of the area in eighteen states had been cleared of barberry. About 200,000 square miles are still partially infested, mostly in areas that are not easily accessible.

Barberry eradication has been accompanied by a marked reduction in losses due to stem rust. This period has coincided with the increasing and widespread use of resistant varieties in the Great Plains. It is this area in which the most severe losses occur. Damage to susceptible common wheat varieties in experimental plots in the spring wheat region as late as 1945 and to durum wheat in 1951 and 1952 showed very clearly that barberry eradication alone is not sufficient to control stem rust in this area. The reason is now known to be the wind-blown spores coming from the overwintering areas in south Texas and northern Mexico. Infection from barberry bushes usually occurs earlier in the spring than that from wind-blown spores, and in some areas these bushes are the principal source of infection. These facts, plus the production of new races of stem rust by hybridization on barberry bushes as discovered by Craigie (1927, 1928), provide sound reasons for continuing the eradication campaign.

2. *Leaf Rust*

Leaf rust of wheat, although more generally and uniformly distributed throughout the humid wheat-growing areas of the world, causes less damage than does stem rust. Formerly, it was most severe in the winter wheat areas of the United States, especially in the East and Southeast. In more recent years, damage has been considerable in the central United States and in Canada on hard red spring wheats. In 1938 it occurred in epidemic force in this area and caused losses up to 30 per cent in several states from Texas to Canada.

Leaf rust does not require infection of an alternate host in its life history, and unlike stem rust it survives the winter on wheat plants, as far north as Maryland. Although the rust can resist cold, it cannot endure high summer temperatures, and, consequently, it often dies during the hot summers of the southern wheat areas. Chester (1939) showed by means of airplane spore traps that viable spores are blown back from the North by the northerly fall winds to infect the winter wheat in the South. At times this infection is so severe that it injures the wheat for winter pasture and causes a poor survival of the crop. Leaf rust thrives during periods of damp weather with temperatures ranging from 50° F. to 60° F. Little or no infection occurs above 80° F.

The most practical method of combating leaf rust is by breeding re-

sistant varieties. This is complicated by the existence of over 130 physiologic races of the fungus. Many races are localized geographically, whereas others are widely distributed. Johnston (1932) found race 9 more prevalent and abundant in the southern Great Plains, whereas races 3 and 5 were more frequently encountered in the Eastern States. Varieties highly resistant to some races may be extremely susceptible to others. Chester and Jamison (1939) reported that certain hybrid selections from KAWVALE × MARQUILLO and HOPE × HUSSAR showed the greatest degree of resistance from the seedling stage to maturity. *Triticum monococcum, Triticum timopheevi,* and most of the durums are resistant. The emmers range from resistant to susceptible. So far, no single known variety of wheat is resistant to all races.

3. *Control of Rusts by Dusting*

Leaf rust and stem rust may be controlled by dusting the crop with sulfur or other fungicides (Lambert and Stakman, 1929). Bailey and Greaney (1926) in Canada found that dusting with sulfur at two- or three-day intervals at the rate of 15 pounds per acre controlled both leaf rust and stem rust and increased the yield 34 bushels per acre. They found (1928) that dusting biweekly with Kolo dust by means of an airplane at the rate of 30 pounds per acre was an effective means of control. The control of rusts by this method, however, is generally too expensive to be practical and especially so if numerous applications are necessary because of frequent rains washing the fungicides off the plants.

4. *Stripe Rust*

Stripe rust (*Puccinia glumarum*) was first recognized on wheat in the United States in 1915 near Sacaton, Arizona, by Dr. F. Kolpin Ravn. Subsequent examinations of herbarium specimens, however, indicate that it was present in this country as early as 1892.

This rust has caused serious losses to wheat in Argentina, China, Great Britain, and the countries of northern Europe, but it has not been a serious threat to wheat in the United States. Bever (1938) tested 317 American wheat varieties for resistance to this disease. The durum wheats were the most resistant, and the club wheats as a group were the most susceptible, with notable exceptions in both groups.

5. *The Smuts of Wheat*

Wheat is subject to attack by three different smuts: bunt or stinking smut (*Tilletia caries, T. foetida,* and *T. brevifaciens*), loose smut (*Ustilago tritici*), and flag smut (*Urocystis tritici*). Of these, bunt is most

widely distributed and most destructive. It is present in practically all regions where wheat is grown.

a. Bunt or Stinking Smut. Three species of bunt are prevalent in North America. The smooth-spored species, *Tilletia foetida,* is more common in north central and eastern North America; both species occur in the western areas, although *Tilletia caries,* identified by its reticulate spores, is more prevalent there (Rodenhiser and Holton, 1945). The life history of the bunt fungus is relatively simple. In most areas, the disease is carried over to the next crop by means of spores on the seed, but in some parts of the Pacific Northwest, the soil becomes infested during harvesting or threshing, and the spores germinate along with the wheat after the fall rains.

Tilletia brevifaciens known as dwarf bunt was first observed in the early thirties (Young, 1935). Dwarf bunt, as its name indicates, stunts the plants severely, and its spores persist in the soil for more than a year, even in the absence of wheat. At harvesting time the combine passes over and misses the infected heads on the dwarfed plants and consequently practically all the dwarf bunt is left in the field. As a result, the soil becomes much more severely infested with dwarf bunt than with common bunt.

Losses in yield due to bunt vary in proportion to the percentage of the plants infected. Spore dust in the air may cause dust explosions and severe fire losses. Smutty seed subjects the grain to a discount of several cents per bushel.

(1) Control of Bunt. Measures for controlling bunt include the use of bunt-resistant varieties, seed treatment, and possibly soil treatment for soil infestation. The first effective attempt to control bunt through seed treatment was made some time after Kühn (1873) developed the copper sulfate or "blue-stone" treatment. Bolley (1897) introduced the formaldehyde treatment for the control of bunt and certain other cereal smuts. Because of its relative cheapness, simplicity of application, and general effectiveness, it replaced the copper sulfate treatment to a great extent and remained the foremost liquid treatment for many years, in spite of its tendency to injure the seed.

Riehm (1914) first described the use of organic mercurial solutions for treating cereal seeds. In 1915 a number of these were marketed in Germany, and a few years later were introduced into the United States. Seed was treated by soaking it for about a half-hour in a 0.3 per cent water solution, after which it was drained and dried. In general, these mercurials were very effective. They caused no seed-injury if properly applied and frequently improved emergence. However, they never came into wide general use.

Darnell-Smith (1915) in Australia described the use of copper carbonate applied in dust form to wheat seed for the control of bunt. This form of seed treatment was later investigated and described by Mackie and Briggs (1923) and soon met with wide popularity in the United States. It eliminated the necessity for soaking the seed and the consequent laborious work of drying it. A serious objection to its use was its tendency to cause nausea when the dust was inhaled. It also occasionally caused injury to drills. In the late twenties Ceresan, a dust fungicide containing 2 per cent ethyl mercury chloride, appeared on the market and soon won wide acceptance as an effective seed treatment not only for preventing bunt but also for eliminating other seed-borne diseases. However, its high cost, 9 to 14 cents per bushel of seed treated, was an impediment to its general country-wide adoption. In 1933 it was replaced by New Improved Ceresan (5 per cent ethyl mercury phosphate). This material was effective when applied at the rate of only ½ ounce per bushel at a cost of less than 3 cents per bushel. It became the principal mercurial seed treatment for cereal seed in the United States. It was generally recommended not only for bunt in wheat but also for the control of other harmful organisms on the seed and as a protectant against certain injurious soil-inhabiting fungi.

Late in 1947 this material was largely replaced by Ceresan M, containing 7.7 per cent ethyl mercury *p*-toluene sulfonanilide, a mercurial equally as effective but somewhat less objectionable in several respects. In the meantime other materials for treating wheat and other seeds appeared on the American market along with new methods of applying them. The slurry method of seed treatment was devised to eliminate the discomfort and hazard of flying dust encountered in applying dust fungicides. This method involves the use of a special treater in which the fungicide is applied to the seed as a water suspension or slurry of about the consistency of buttermilk. From 0.5 to 1 per cent of water is added to the seed along with the fungicide, but it soon evaporates so that the seed may be sacked and stored immediately after treating. However, some dust is given off when the seed is handled after it has dried.

The fungicide Panogen appeared on the market in the United States and Canada in 1948. It is a "quick-wet" treatment and is applied as a concentrated liquid at the rate of ¾ fluid ounce per bushel in a treater constructed especially for that purpose. It is widely used in certain Midwestern wheat-growing areas, where a considerable number of treaters have been installed. It controls bunt effectively and improves stands and yields.

More than a dozen fungicides for the control of seed-borne diseases of wheat were marketed in 1952. Most of them may be applied either

as dusts or slurries. With these effective fungicides available, it should be possible to eliminate ordinary bunt as a wheat hazard except in certain areas of the Pacific Northwest where bunt spores are present in the soil. Seed treatment will not prevent infection from this source whether caused by ordinary bunt or dwarf bunt.

Experiments are in progress (Holton and Jackson, 1952) to determine whether infection from soil-infesting spores can be prevented by applying certain fungicides to the soil along with the seed. Hexachlorobenzene and pentachloronitrobenzene have shown some promise of being effective for this purpose when dusted into the furrows along with seed.

The incidence of bunt in the United States has been considerably decreased by the use of resistant varieties. The development of such varieties is complicated, however, by the existence of physiologic races of the bunt fungi first suggested by Faris (1927). Rodenhiser and Holton (1937) identified eight distinct races of *Tilletia foetida,* the smooth-spored species, and eleven races of *Tilletia caries.* Holton and Suneson (1942) tested the reaction of eighty-three varieties and hybrid selections of winter wheat to bunt in uniform nurseries at eleven locations in the western United States and at one in the East, from 1932 to 1940. Eight of these selections averaged 1 per cent or less infection. They were from crosses between RIDIT and RELIEF, RIDIT and HOHENHEIMER, HUSSAR and HOHENHEIMER, and ORO and TURKEY–FLORENCE. One selection from a HUSSAR × HOHENHEIMER cross was found to be resistant to all known bunt races.

b. Loose Smut. Loose smut of wheat is less common than bunt and causes less severe losses. Also it does not affect the marketing quality of wheat as does bunt. Loose smut, however, is more difficult to control by seed treatment or by the development of resistant varieties because of its peculiar life history. The spores from smutted heads are carried by air currents to open wheat flowers, where they germinate and infect the ovary. When the wheat kernel ripens, the smut mycelium remains in the wheat embryo in a dormant condition and resumes growth when the wheat seed germinates. The mycelium then invades the growing point of the seedling and when the wheat head begins to form, it replaces the kernels with a mass of black chlamydospores.

The location of the smut mycelium within the embryo of the wheat kernel makes control of the disease through seed treatment very difficult. In general, chemicals that will kill the smut fungus in the embryo will kill the embryo also. Jensen (1889) discovered that immersing presoaked wheat seed in water at 129° F. for ten minutes kills the smut mycelium in the seed but does not kill the embryo. The temperature and

the period of exposure are very exacting. If they are not observed carefully, either the smut mycelium will not be killed or the embryo will be killed along with it. This method of seed treatment is difficult and cumbersome and not suitable for the average farm or for large quantities of seed. Its use is generally restricted to the treatment of a few bushels of seed by competent operators. This seed is then sown in an isolated plot to avoid infection from other wheat fields and the crop is used to produce smut-free seed. Tapke (1931) demonstrated that infection depends upon a high relative humidity at flowering time.

Identifying physiologic races, studying their prevalence, and breeding for resistance to loose smut were greatly hampered for a time by the slow and laborious methods necessarily used for inoculating individual flowers. Moore (1936) devised a method for inoculating an entire head in one operation by using a partial vacuum and a spore suspension. Other improved methods have since been described. Moore (1942) reported the existence of five races and Bever (1947) found eleven "pathologically distinct" races on 52 collections from fifteen states.

c. Flag Smut. Flag smut was first found in the United States in Madison County, Illinois, in May, 1919, and in adjacent St. Louis County, Missouri, in 1922. Since then it has appeared in northeastern Kansas, and in 1940 it was found in Klickitat County, Washington. It is believed that this disease was introduced into the United States from Australia in 1918 in an importation of 5,500,000 bushels of wheat. This wheat was intended for milling purposes only, but some of it inadvertently may have been used for seed, since in some manner flag smut spores were spread to the soil of nearby wheat fields.

Flag smut occurs only in winter wheat areas where a mild winter climate prevails and where continuous wheat culture is practiced along with the use of susceptible varieties. Infection may be due to spores on the seed or to spores left in the soil from a previous crop.

Seed treatment with fungicides, such as are effective in bunt control, will prevent infection from seed-borne spores but not from spores in the soil. A combination of seed treatment, proper crop rotation, and the use of resistant varieties should eliminate flag smut as a serious threat to wheat culture in the United States.

Holton and Johnson (1943) tested collections of flag smut from Kansas and Washington on 100 varieties of wheat and reported the existence of two distinct physiologic races. Certain selections from ORO × FEDERATION 38 and from ORO × FEDERATION 40 were highly susceptible to the Washington collection and immune from the Kansas collection. No varieties tested were resistant to the Washington collection.

6. *Wheat Mildew*

Powdery mildew damages wheat when extended periods of cool cloudy weather occur at the time of tillering and internodal elongation of the wheat plants. It may greatly reduce the size of the kernels and also the yield of grain. Control measures, as in the case of rust, are limited to the use of resistant varieties and to dusting the crop with fungicides, because the disease is spread by air-borne spores. Mains (1924) tested 650 varieties and strains of wheat for susceptibility to mildew and found six common wheats, NORKA, CHUL, HURON, RED FERN, and SONORA, and one strain of MICHIGAN AMBER practically immune in the seedling stage. KHAPLI and VERNAL emmer, and EINKORN were highly resistant. Later Mains (1933) suggested the presence of physiologic races.

Taylor, Rodenhiser, and Bayles (1949) reported the existence of three races of wheat mildew in the eastern United States and found NORKA and AXMINISTER resistant to races 1 and 3 and susceptible to race 2. Five other spring varieties were found (CHUL, DIXON, HOPE, HURON, and SONORA) resistant to all three. Lowther (1950) differentiated nine distinct races on AXMINISTER, ULKA, CHUL, HOPE, and NORMANDIE.

Neatby (1936) made the interesting discovery in crosses between H-44-24 and MARQUIS that the lines susceptible to mildew were resistant to race 36 of stem rust, and conversely, the lines susceptible to this race of stem rust were resistant to mildew. This probably is due to a close genetic linkage.

Sulfur dusts and other fungicides used in controlling stem and leaf rusts also control powdery mildew, and the problems involved in their application for rust control apply also to this disease.

7. *Miscellaneous Diseases*

Other diseases cause considerable damage at times to wheat in the United States. Many of these diseases were largely overlooked in the first twenty years of the century because little was known about them. The urge to produce more food before and during the first World War turned attention to some of the more obscure causes of poor wheat stands and yields. Plant pathologists studied critically the various diseases of wheat, such as "take-all," scab, mosaic, bacterial blight, root rot, and others, with regard to their causes and attempted to find preventive measures. Improved cultural methods, superior seed, resistant varieties, better fertilizers, quarantine restrictions, and fungicides were employed with varying results.

a. Scab. Scab first came into prominent notice as a serious wheat disease about 1915. This disease causes seedling blight and also attacks

the heads soon after heading, resulting in shrunken or aborted kernels. Surveys made in 1919 placed the estimated losses of spring and winter wheat due to this disease at 80 million bushels. Similar costly epidemics occurred again in 1928 and 1935. Damage was heavy in several other seasons in Illinois, southern Wisconsin, southern Minnesota, Iowa, Maryland, Virginia, and North Carolina.

Extensive investigations (Adams, 1921; Holbert *et al.*, 1919; Dickson, 1921, 1923) were carried out on this disease for several years by workers in several state experiment stations in an effort to find effective and practical control measures. Measures for combating it resulted largely from the studies of Dickson, Johnson, and their co-workers at the University of Wisconsin. It was found that severe infection depended on an abundance of spores and on warm humid weather during the period of heading and flowering.

Corn proved to be very effective in furnishing spore inoculum when it preceded wheat in the rotation. The old corn stalks left in the field frequently are heavily infected with the fungus and produce spores in abundance. The disease may also be carried over in wheat seed. It was found that thorough cleaning of the seed to remove light, shriveled, infected kernels, along with the use of a mercurial seed treatment, largely eliminated this source of infection.

Scab is caused by a number of Fusarium species, chiefly *F. graminearum* and *F. culmorum*. Some species are more abundant in some sections, and other species predominate in other sections.

The growth of these fungi in the developing kernels results in the formation of poisonous compounds that act as strong emetics in man, dogs, horses, pigs, and other animals with similar digestive systems. This poisonous substance (Dickson *et al.*, 1930), which seemingly contains glucosides or basic nitrogen compounds, affects the nerve center controlling the stomach muscles and causes violent nausea, dizziness, loss of appetite, and general digestive disturbance. Ruminating animals and poultry are not affected.

Wheat varieties vary in susceptibility to scab, but no highly resistant varieties have yet been discovered. Christensen and Stakman (1927) subjected over 250 varieties of Triticum species and many selections and crosses to an artificial epidemic of scab. The severity of seedling blight and head blight varied with the date of sowing and date of heading, and with conditions of temperature and humidity at flowering time. No varieties tested were immune. MARQUIS, KITCHENER, and RED BOBS were most susceptible. GLYNDON FIFE, HAYNES BLUESTEM, and PRELUDE were resistant. PRESTON was resistant for four years, after which it was heavily infected. This suggests the appearance of a different physiologic

race, or possibly of another species of Fusarium that causes scab. Most durums were susceptible, but a few were quite resistant.

b. Anthracnose. The Anthracnose disease of wheat and other cereals was first described by Selby and Manns in 1909. It is important at times in the soft red winter wheat area and in the rye area of the north central United States. It attacks all the cereals and many grasses, and because it is saprophytic on residues of these crops, its persistence, severity, and spread are encouraged by continuous cereal-grass culture. The causal fungus may be seed-borne, and effective seed treatments are therefore advisable to prevent primary infection of the seedlings, especially if the seed is sown in soil free from infected crop residues. Damage is reduced by crop rotation and improved soil fertility resulting from the use of legumes in the rotation, by plowing under cover crops, and by a proper balance of phosphate and potash.

c. Wheat Mosaics. (1) Soil-borne mosaic. In 1919 a new disease was found in HARVEST QUEEN wheat near Granite City, Illinois. At first it was thought to be caused by a fungus, but the causal organism could not be isolated from the diseased plants. In 1923 McKinney tentatively assigned the descriptive name "wheat rosette" to the disease because of the abnormal appearance of diseased plants.

In later studies McKinney (1925a) observed that the leaf mottling and the rosette condition were manifestations of a transmissable mosaic disease, caused by a virus. He found that it persisted in gumbo or sandy clay soils for as long as six years. In some varieties it caused leaf mottling only, and in others both rosette and mottling. The disease has since been known as "soil-borne wheat mosaic." It is the first known soil-borne mosaic. McKinney (1937) demonstrated that it is not transmitted through the seed or by insects and that it could be controlled by resistant varieties.

Koehler *et al.* (1952) reported the presence of this disease in forty-three counties in Illinois. The resistant varieties of soft red winter wheat, ROYAL, VIGO, SALINE, SENECA, and NEWCASTER, are recommended for southern Illinois. Further north the hard wheats PAWNEE and WESTAR, are suggested, although they are not entirely resistant. The winter hardy soft wheats, ROYAL, PRAIRIE, and SALINE, are also recommended for this area.

Soil-borne wheat mosaic has been found also in Indiana, Virginia, Maryland, North Carolina, South Carolina, and Missouri. It is no longer a serious threat to wheat culture because resistant varieties of good quality and yield have been developed.

(2) Streak mosaic. Wheat is attacked also by a streak mosaic, which is not soil-borne and the manner of spread of which has not yet been

determined. It was first observed in Kansas and Nebraska in 1922 and again in some Kansas counties in 1930 and 1932. The most serious outbreak occurred in Kansas in 1949. Injury in different fields ranged from a trace to 100 per cent. In Lane County, for example, the over-all loss was estimated at 26 per cent. This wheat mosaic is now found also in parts of Oklahoma, South Dakota, and Colorado. Efforts are being made to determine its manner of spread and to develop resistant wheat varieties.

d. Crown, Foot, and Root Rots. Several fungi are associated with diseases that attack the crown and roots of wheat. Injury is usually confined to parts of the plant that are underground or near the surface of the soil, although symptoms may be evident in other parts of the plant.

Examples of these diseases are: Take-all, Pythium root rot, Helminthosporium crown and root rot, Snow mold, Typhula blight, Rhizoctonia blight, frost injury, and foot or culm rot caused by species of *Cercosporella* and *Leptosphaeria.* McKinney (1925b) and Sprague (1944) have described a number of the foot rot diseases of wheat commonly found in the United States.

Take-all occurs most commonly in the drier winter wheat section of southwestern and northwestern North America. It is associated with porous alkaline soils where winter wheat culture is continuous. The name "take-all" is generally associated with the disease caused by *Ophiobolus graminis,* but often it is applied to a complex of diseases attacking the roots, crown, and basal culm tissues of wheat and other cereals. Finding the causal fungus on the diseased plants is the only sure means of identifying the real take-all disease. There are no varieties of wheat highly resistant to take-all. Control measures are restricted to crop rotation plus an abundance of available phosphate and potash.

Pythium root rot, caused largely by *Pythium arrhenomanes,* is widely distributed and attacks not only wheat but other crops, including corn, sorghum, and sugar cane. The causal organisms are soil-borne, and no adequate method has been devised to prevent the damage they inflict on wheat.

Other root and crown rots are caused by species of *Helminthosporium* (especially *H. sativum*), *Typhula, Rhizoctonia,* and *Cercosporella.* They are all soil-borne, and most of them are able to thrive saprophytically on crop residues in the soil. They can be combated (Dickson, 1947) to some extent by crop rotations that include legumes, by late sowing of winter wheat, and by a balanced soil fertility. Snow mold (*Typhula idahoensis* and *Fusarium nivale*) in recent years has caused considerable damage in western Idaho and in central Washington.

Sprague (1944, 1946) found that *Helminthosporium sativum* is the

most important root fungus attacking wheat in North Dakota. The extent of injury by this and other fungi is largely dependent on environmental conditions such as temperature, moisture, soil type, and cultural practices.

A summary of the recommendations made by various investigators for the reduction of injury due to the root and foot rots of wheat would include the use of the best available seed, early seeding of spring wheat, growing wheat in rotation with legumes, and the use of summer fallow and phosphate fertilizers in certain areas.

The great advances made in recent years in the production of effective fungicides suggests the possibility of development of soil treatments that will exterminate the harmful soil fungi to a great extent without seriously affecting the beneficial organisms in the soil.

A possible means of control still in the experimental stages involves the use of chemicals which are absorbed by the plants and which inhibit or prevent the development of pathogens and do not injure the host plant. The method known as chemotherapy, though not used on wheat, has given favorable results in control of certain diseases of trees, fruits, and ornamentals (Howard, 1941; Zentmeyer *et al.*, 1946; Stoddard, 1947, 1951; Dimond *et al.*, 1952; Horsfall and Dimond, 1951, 1952).

VII. Control of Insect Pests of Wheat

Wheat is subject to attack by numerous insect pests from the time it is seeded until it is placed on the consumers' table in the form of bread or other products. Severe losses occur somewhere every year and in nearly all areas in some years. Research has played an important role in keeping losses at a minimum, but in no case can it be said that an insect pest has been eliminated or is completely under control. Total damage tends to increase as the acreage of wheat increases because of the build-up of insect populations to infest succeeding crops and spread to other areas. In several cases, native insects that did little or no damage to the wild grasses on which they lived increased enormously when the land was broken up to become a factor of major importance to cultivated crops, including wheat.

The principal insects that attack growing wheat are the Hessian fly, wheat jointworm, wheat strawworm, wheat-stem sawflies, several species of grasshoppers, greenbugs and other aphids, chinch bugs, wheat-stem maggot, wireworms, cutworms, and stink bugs. A number of species seriously damage wheat in storage. Some insects such as the chinch bug and cutworms attract attention principally because of damage to corn and other crops, but they also attack wheat. Others such as the Hessian

fly, jointworm, and sawfly attack wheat only or principally. Some are native to the United States and have found in cultivated crops ideal conditions for their development and spread. Others, including some of our most destructive pests, have been introduced from foreign countries. Build-up of populations and damage by all of them are affected greatly by weather and other environmental conditions. Often they are quiescent for a number of years only to become agents of disaster when conditions become favorable. In practically all cases, areas of infestation and losses have increased more or less continuously during the last fifty years.

Control is often difficult or impractical even when effective methods are known. For example, an insect that causes a consistent but small percentage loss may account for a very material decrease in production for the country as a whole and yet mean very little to the individual farmers. This is especially so if control measures involve inconvenient or costly changes in management or cultural practices. Sometimes such changes invite losses from other causes that are more important. It is for these reasons that known control measures sometimes are used very sparingly or not at all. Another difficulty stems from the fact that in many cases concerted community action is necessary in order to achieve effective control. It is only when losses become heavy, as they often do in particular localities, that serious attention is given to control measures. This means that research must and does aim to develop methods of control that may be incorporated as a part of the general cultural pattern insofar as is feasible, and to develop those that are simple and inexpensive when special measures are necessary.

Such research has included especially investigations of insecticides, cultural practices, life history studies including egg-laying and feeding habits, and breeding resistant varieties. Methods of applying insecticides have had much attention. Correlating insect epidemics with weather and other environmental conditions has provided information that is very useful for predicting or forecasting outbreaks and thereby preparing for them. Breeding resistant varieties has had a prominent place in research to control insects only in relatively recent years.

1. Hessian Fly

The Hessian fly is without doubt the most destructive insect pest of wheat. The estimated loss in a single year has amounted to as much as \$100,000,000. Haeussler (1952) estimated the annual loss in the United States in 1945 at \$37,000,000.

The Hessian fly occurs in California and in the Pacific Northwest and generally from western Kansas and Nebraska the Atlantic seaboard

and from northern Oklahoma to Minnesota. It is most common in winter wheat but sporadically damages spring wheat. It was first discovered on Long Island in 1779 in the vicinity of Lord Howe's camp of three years before. It is thought by many to have been brought in in bedding used by the Hessian soldiers included in the British army; hence, the name. It spread westward almost as rapidly as did wheat, reaching Kansas in about 1871 (McColloch, 1923) and the West Coast by 1884.

Cultural practices, including destruction of volunteer wheat plants, plowing under of stubble, and late seeding, which had developed largely as a result of general observation were the commonly recommended control practices before the turn of the century. Late seeding, according to Bidwell and Falconer (1941, p. 96), was recommended as early as 1811. These methods are still used. Other measures now known to be ineffective or objectionable or both were also frequently recommended. These included pasturing, burning stubble, and the use of decoy or trap crops. Varieties of wheat believed to be less susceptible to the Hessian fly than others were recommended in the nineteenth century but not until the early 1940's were varieties available in which fly resistance actually had been bred as an important character.

Date-of-seeding tests with wheat were conducted systematically and for several years in Indiana and Ohio and perhaps other states beginning as early as 1887. Based on these tests and observations on time of emergence of Hessian fly in the fall, a map of Ohio showing approximate dates for safe planting in various parts of the state was published by Webster (1899) of the Ohio Station in 1899. In the following year, A. D. Hopkins (1900), using these data and his own observations in West Virginia as starting points and making use of the relation between altitude and latitude on the one hand and certain phenological data on the other, constructed a similar map for West Virginia. These probably were the first maps to be published showing "safe" or "fly-free" dates of seeding. The West Virginia map was probably the first practical application of the principles that later became the well-known Hopkins bioclimatic law.

Extensive date-of-seeding tests since conducted by the Bureau of Entomology and Plant Quarantine and by the state agricultural experiment stations have provided the information for similar maps for all Hessian fly-infested areas of the United States. Although the general principles have not been changed, the application has been improved and refined. One improvement in particular stems from recognition of the fact that the best dates for seeding fluctuate considerably from year to year, depending on weather conditions and the prevalence of Hessian fly. Timely information regarding these factors supplied by entomolo-

gists and county agents for each infested area has aided materially in preventing serious losses.

Seeding on or after the fly-safe dates has been used extensively in all Hessian fly-infested areas. It has not been fully effective, partly because unexpected delays in seeding caused by unfavorable weather invite losses from other causes and hence farmers tend to seed earlier than the fly-safe dates, especially when infestation is light. Concerted community action, sometimes difficult to achieve, is also necessary for fully effective control. Other measures of control have therefore been sought.

The most recent and theoretically, at least, the most satisfactory of any control measure is the use of resistant varieties. Obviously, of course, success here depends on the availability of varieties that not only are resistant to Hessian fly but also satisfactory in other respects and adapted to the areas where they are to be grown. Producing such varieties has, as would be expected, proved to be a difficult and time-consuming process.

The best examples of resistant varieties now in use by farmers are the hard winter varieties PAWNEE and PONCA and the California varieties BIG CLUB 43, POSO 44, and POSO 48, described in Section IV. 4b. The latter are credited with practically eliminating the Hessian fly in the Montezuma Hills section of California, and PAWNEE is believed to be responsible for a very material reduction of Hessian fly in eastern Kansas and contiguous areas. PONCA wheat, released by the Kansas and Oklahoma Agricultural Experiment Stations in 1951, is the most resistant variety of hard red winter wheat available commercially.

Especially significant in relation to breeding other resistant varieties is the discovery at the Indiana Station of an unusually high degree of resistance in a durum wheat introduced from Portugal by the United States Department of Agriculture. This resistance, unlike that found in PAWNEE and other commercial varieties, appears to be effective in all areas of the United States and at high temperatures. Much progress has been made in transferring this resistance to commercial varieties of common wheat, but the work is slow because of sterility and linkage such as is invariably encountered in crosses of common and durum wheat.

2. *Grasshoppers*

Perhaps the most spectacular and useful research relating to the control of wheat insects is that concerned with the control of grasshoppers, including Mormon crickets. These insects, of course, attack all crops, including wheat, and are of particular concern here since they are most destructive in areas where wheat is an important crop. According to

Hyslop (1938), severe outbreaks occur in the United States at least once in every ten years and each may last from one to six years. On the basis of reports by entomologists from twenty-three of the most heavily infested states, Hyslop has estimated the annual loss from all crops at about $25,000,000 per year for the ten-year period 1925–1934. Haeussler (1952) recorded the estimated loss in eighteen states in 1950 at nineteen million dollars. Infestation and damage are greatest in those areas where the annual rainfall is about 25 inches or less, partly because dry climates favor the build-up of large populations and partly because there is less vegetation other than cultivated crops on which grasshoppers may feed.

The most notorious outbreaks were those of the Rocky Mountain grasshoppers, or locusts, as they were then called, during the developmental stages of agriculture in the Great Plains. This particular species disappeared about 1880 or were replaced by similar or identical species with a different name. Three of the most important species in the west today are the lesser migratory grasshopper, the differential grasshopper, and the two-striped grasshopper. Depopulation of large sections of the southern Plains in the 1880's and 1890's was in part due to these and other species. Recurring outbreaks, as indicated above, continued to be a feature of Great Plains agriculture until new methods of control were developed in recent years.

Various methods to control grasshoppers have been used. The first ones were mechanical, such as hopperdozers, and for the nonflying Mormon crickets, trench, wood, or sheet iron barriers with pits at frequent intervals in which the insects were collected and killed. Poison bait, first used in the San Joaquin Valley of California in 1885, was an important forward step. This device worked surprisingly well but was not consistently effective because the grasshoppers would not always take the bait. An important improvement was almost immediately made by substituting wheat bran for middlings, and numerous subsequent attempts were made to make the bait more attractive by adding fruit juices, molasses, banana oil, or flavoring of various kinds. In general, however, according to Packard (1942), the increase in effectiveness obtained with such attractants was not enough to offset the additional costs. A more important achievement was the reduction in costs by diluting the bran with relatively inert materials such as sawdust and cotton seed hulls.

An interesting and significant discovery was the fact that Mormon crickets, in contrast with other grasshoppers, would not eat bait containing arsenic compounds but readily took those containing the equally poisonous sodium fluosilicates. Since grasshoppers readily took to either,

the cost of baiting was greatly reduced and the general effectiveness of baits was greatly increased. The use of the motorized truck to transport and spread poison bait, power mixing machines and spreaders, and the adaptation of the airplane for distributing poison baits greatly extended their use. The reduction in costs made control by poison baits practical on a large scale, and they were used extensively for many years.

Without doubt, the most significant and far-reaching research achievements of all time relating to insect control methods were the discovery and use of the new insecticides aldrin, chlordane, toxaphene, and others. Incredible though it may seem, as little as 2 ounces of aldrin per acre, applied as a spray or dust by airplane or ground equipment, will, under favorable conditions, result in almost complete destruction of grasshoppers on the treated areas, and the residual effects are often sufficient to protect the crop from later invasions. Sprays in general are less expensive and more effective than dusts, and they have many advantages over baits. As a result of this development, sprays and dusts have practically replaced baits for the control of grasshoppers. Most useful also in relation to airplane spraying is the fact that good distribution may be achieved with as little as a gallon or less of spray liquid per acre. This means that a plane may spray a hundred acres or more with one loading. It is not unusual to treat 1,000 acres per day per plane, and large planes capable of treating 10,000 acres per day have been equipped for the purpose. This, of course, is many times as rapid as treating with ground equipment.

Airplane spraying with the new methods is sufficiently inexpensive that range and wastelands on which the large migratory swarms of grasshoppers once originated may now be treated. Some 12,000,000 acres of range and cultivated land have been so treated during the past few years with the result that migrations have been all but stopped, and control is now largely on a preventive basis. As an example of control at the source of infestation, the area infested with Mormon crickets was reduced from some 19,000,000 acres in 1938 to about 116,000 acres in 1949. Incidentally, the new insecticides and methods are used also for the control of other insects.

3. *Wheat-Stem Sawfly*

Research designed to develop methods of controlling wheat-stem sawfly is an excellent illustration of the interdependence of different countries and of the value of co-operation in developing control methods. The most promising method for controlling this insect is by the use of resistant varieties. The only resistant variety so far grown by the farm-

ers in the United States is the spring variety RESCUE, produced by Canadian research workers and introduced into the United States in 1947.

The wheat-stem sawfly is indigenous to the Great Plains, where it has lived for untold centuries on wild grasses. It was collected in wheat in Canada as early as 1895, in Montana in 1900, and in North Dakota in 1906. Infestation in Montana and Saskatchewan in 1908 was sufficient to cause some alarm and likewise in North Dakota in 1916. It has been a serious pest in Canada since the early 1930's, and sporadic outbreaks have continued in Montana and North Dakota. The insect appears to have become firmly established in both states in about 1941 or soon thereafter and the infested area has increased nearly every year. Platt and Farstad (1946) regard the wheat-stem sawfly as a major limiting factor in the production of wheat in many areas of the Prairie Provinces of Canada and have estimated the annual losses at 20,000,000 bushels. The estimated loss in the United States in 1951 was almost 5,000,000 bushels. In the United States it has been most destructive in spring wheat but in recent years has caused severe losses in winter wheat in central Montana. It has not as yet been a serious pest in the main winter wheat belt of the United States. The use of strip cropping in Montana and Canada, in which a narrow strip of wheat alternates with a strip of fallow, provides ideal conditions for the sawfly to migrate from stubble to the growing crop and is believed to have been a factor in establishing this insect as a major wheat pest in recent years.

The RESCUE variety was produced from a cross of the Canadian variety APEX with another known as S-615, which was originally from Portugal but was secured by Canadian workers from New Zealand. In the United States RESCUE has yielded somewhat less than other varieties in the absence of sawfly and for other reasons is not regarded as completely satisfactory. It has reduced losses in the sawfly-infested areas, however, and is grown extensively by Montana farmers for that reason. Additional sources of resistance have been discovered in recent years, and breeding is under way to incorporate these into commercial varieties.

4. *Other Insect Pests of Wheat*

Control of some insect pests of wheat has not been conspicuously successful. In some cases, losses suffered by individual farmers have been small or they have been infrequent, which means that it has been difficult or quite impossible to get the continuing support that is often necessary for successful research. Nevertheless, much has been learned in the past fifty years that will be most useful if serious outbreaks do occur and for most insect pests methods of control now recommended and

sometimes used are, without doubt, far superior to those used in the nineteenth century.

As a result of recent research, for example, about 1,000,000 acres of wheat was sprayed, mostly with parathion, to control greenbugs in Oklahoma in 1950 and 1,800,000 acres in the state were treated in 1951. This is the first successful method developed for the control of this pest, credited with the destruction of 50,000,000 bushels of grain or more in the southern Great Plains in 1907 and again in 1942, and with that of 25,-000,000 bushels in Oklahoma in 1950 (Haeussler, 1952), with several serious outbreaks in other years.

New insecticides have also been found useful in the control of the armyworm, fall armyworm, wireworm, stored-grain insects, and others. Chemical dust barriers of which the active ingredients are DDT or dinitro compounds have been found useful supplements to other methods in preventing the migration of chinch bugs from small grains to corn and sorghum.

Studies of the taxonomy, life histories, and egg-laying and feeding habits, have been most useful in suggesting control methods. Knowledge of these for many insects was completely lacking or was very incomplete fifty years ago. Wade and St. George (1923), for example, state that false wireworms have often been confused with other species, and hence not recognized as the destructive pests they really are. The reliability of forecasts and warnings of destructive epidemics so necessary for organized large-scale control campaigns has been greatly improved in recent years as a result of more complete information regarding the relation of insect populations to weather and other environmental factors.

Among the more significant discoveries of recent years in relation to future control is the resistance or tolerance of varieties of wheat to most insects that attack it. Jones (1943), for example, points out that varieties of wheat have been reported as resistant or tolerant to at least fifteen insects besides Hessian fly. Painter (1951) has published an excellent review of the attempts to breed varieties of wheat resistant to various insects. Briefly, the principal achievements are the varieties mentioned above that are resistant to Hessian fly and to the wheat-stem sawfly, and the discovery more or less incidentally of several sources of resistance, as mentioned by Jones. Efforts to transfer newly discovered genes for resistance to commercial varieties will be made at the first opportunity.

Acknowledgments

The experimental data on which most of this paper is based were obtained by various agencies, principally the various state agricultural experiment stations in those states in which wheat is an important crop; by the Bureau of Plant Industry, Soils, and Agricultural Engineering, usually in cooperation with the state agricultural experiment stations; by the Bureau of Entomology and Plant Quarantine; and by the Grain Branch, Production and Marketing Administration, of the United States Department of Agriculture. Much of these data have been published and are referred to in the text. The use of unpublished data is, in general, referred to in footnotes to tables or in text. Permission for the use of these data is gratefully acknowledged. The authors are indebted to various individuals for providing data, and for assistance in assembling data and in reviewing the manuscript. Among these are E. R. Ausemus, B. B. Bayles, C. C. Fifield, K. F. Finney, J. H. Martin, L. P. Reitz, C. A. Suneson, and O. A. Vogel, of the Bureau of Plant Industry, Soils, and Agricultural Engineering; and numerous staff members of the various state agricultural experiment stations. The authors are also indebted to the Division of Cereal and Forage Insect Investigations of the Bureau of Entomology and Plant Quarantine for suggestions and criticisms of the section on the Control of Insects of Wheat. Limitations of space and time have prevented the use of many suggested additions to this paper, including important contributions relating to soil chemistry and soil physics, genetics and cytology, plant pathology, plant physiology, and cereal chemistry.

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The Soil Organic Fraction

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CONTENTS

I. Introduction

Recognition of an organic component of soil dates back to antiquity, and during the development of soil science a great deal of time and effort has been devoted to the investigation of its nature and properties. A voluminous literature on the subject has been built up over the years, but in spite of this it cannot be said that present-day knowledge of the soil organic fraction is much better than rudimentary. As Norman (1942) pointed out, much of the published material is fragmentary and cannot be fitted together to give an over-all picture except perhaps in rather dim outline. In spite of the difficulty of integrating soil organic

matter literature into a coherent whole, much practical information on the subject has been accumulated, and its importance in relation to soil fertility and physical condition is widely recognized. Many of the "what?" questions have been answered, although most of the "hows?" and "whys?" remain to be explained. It is known that the organic fraction has a profound effect upon the structure of soils and that the deterioration of structure which accompanies intensive tillage is usually less rapid in soils of relatively high organic content. The absorption and retention of water, the reserves of exchangeable bases, the capacity to supply nitrogen, phosphorus, and some of the minor elements to growing plants, and the adequacy of aeration and other properties of soils are all dependent in some degree upon the organic fraction.

In recent years there has been a tendency in some quarters to attribute very remarkable properties to soil organic matter, and claims have been made for its effects on plant growth which border on the fantastic. For the most part these claims are without basis in fact and are not supported by the sort of experimental evidence which can bear close scrutiny. Since the small amounts of organic matter in mineral soils exert an influence on chemical and physical properties far out of proportion to their percentage by weight, there is ample justification for emphasis on the importance of this fraction in practical agronomy as well as in agronomic research, without attributing to it the properties of a panacea for all causes of poor plant growth.

II. Formation Processes

As a component of soils the organic fraction is the resultant of a number of complex formation processes characteristic of the environment in which it is found. Residues of the vegetative cover might be termed the parent material from which it is formed. By means of two processes, both of which are due chiefly to the activities of microorganisms, organic matter characteristic of a given soil is produced. The first of these processes is decomposition of plant residues with resultant modification of their chemical composition and properties; the second is synthesis of new microbial cells which in turn die and are decomposed by other microorganisms. That the type of plant residues returned to the soil varies greatly from one place to another is obvious to everyone; what is not so obvious is that the microbial population of soils varies not only with geographical location but also with position in the profile. For example, Gray and McMaster (1933) found biological activity in the leached horizons of certain Podzols to be only about 4 per cent of that in the organic horizons, and Gray and Taylor (1935) were able to

demonstrate marked contrasts in biological activity at different levels between Podzols and a virgin clay soil. Comparison of the potential activity of populations in profiles of several soil types led Newman and Norman (1941) to conclude that the soil population is directly a characteristic of its environment and not readily subject to change. The data of Vandecaveye and Katznelson (1938, 1940) support this conclusion.

Plant materials from which soil organic matter is formed have some similarity in their major structural constituents and in the rates at which they decompose. Numerous investigators have confirmed Hebert's (1892) early observation that lignin and protein are the fractions which accumulate after the other components are largely decomposed, although it is improbable that these are unchanged themselves during the decomposition process. Alterations are effected which may make the lignin and protein quite unlike their counterparts in undecomposed plant tissue.

During breakdown of plant residues in soil large numbers of microbial cells of various kinds are elaborated which exist for only a short time before being themselves subject to decomposition by other microorganisms. The proportion of the soil organic fraction consisting of living microbial cells is very difficult to determine, but Russell's (1950) estimate of 1–2 per cent of the organic matter is probably conservative. Certainly a much larger fraction of the total is microbially derived and somewhat different from plant residues in its chemistry.

In view of the diversity of the organic materials which find their way into the soil and the variety of soil populations which also contribute to what is commonly called humus, it would be surprising indeed if the soil organic fraction everywhere had a common composition. The fragmentary nature of soil organic matter literature is no doubt due in part to the fact that this fraction in a Podzol, for example, may be very different from that in a Prairie Soil or a Sierozem, even though called by the same name in each case.

III. Distribution in Soils

1. *With Respect to Climate and Vegetation*

The quantity of organic matter in soils as a function of climate has been studied by Jenny (1930, 1941), and the subject has been reviewed recently by Ensminger and Pearson (1950) in Volume II of this series. The relationships expressed by Jenny are applicable to loamy grassland soils of the central United States; in general terms the Jenny formula indicates that at constant temperature soil nitrogen increases logarith-

mically with increasing moisture, whereas if moisture is kept constant, soil nitrogen declines exponentially as the temperature rises. Jenny (1941) points out that such soil-climate functions enable one to visualize approximate major trends at the expense of local details. When applied to specific situations, the theory frequently does not hold; in general, it is not applicable where the dominant influence of climate on plant growth and organic matter decomposition is not clear-cut, as, for example, when soils are brought into cultivation and the soil-climate equilibrium is disturbed. Soils long in cultivation eventually attain a new equilibrium level of organic matter which is usually, though not always, lower than that which existed in the virgin state. In Europe, where most of the arable soils have been in cultivation for a long time, the climate-organic matter relationships are not at all apparent. Soil drainage is also an important consideration in any local situation. Where drainage is poor, organic matter accumulates regardless of climatic effects, owing to retardation of the decomposition processes.

Many tropical soils in particular do not have the very low organic matter levels which would be predicted by southward extrapolation of the soil-climate relationships found in the United States. Jenny *et al.* (1949) observed that many Colombian and Costa Rican soils are rich in nitrogen and organic matter, particularly in comparison with California mountain soils. They found that the annual production of organic matter in the form of leaves and twigs was much greater in tropical than in California forests; however, decomposition rates of Colombian forest soils were calculated to be much more rapid. In a later publication Jenny (1950) attempted to reconcile these observations with his earlier work on United States soils by explaining that, whereas decomposition of surface litter in tropical soils proceeds rapidly, that of organic material which becomes incorporated in the mineral soil appears to be slow. This, combined with the abundant production of vegetation, would account for organic matter accumulation within the profile. Jenny suggests calcium deficiency as a possible explanation for the inhibiting effect on decomposition. Ensminger and Pearson (1950) have suggested that the available phosphorus content of these soils may be too low to support an active microbial population. It is difficult to conceive of a situation in which nutrient elements in surface litter are adequate to permit rapid decomposition, while in the soil directly underneath, from which the leaves and twigs originally obtained their nutrients and to which the nutrients are returned after decomposition of the litter, there is an acute shortage of these nutrients. The fact that these soils can produce luxuriant vegetation is incompatible with the view that microorganisms are inhibited by nutrient deficiency.

Recently Smith *et al.* (1951) have called attention to the relatively high organic matter contents of Puerto Rican soils, which compare favorably in this respect with the best soils of the temperate regions. The high organic matter levels can be maintained even under intensive land use. These authors believe that the absence of killing frost is chiefly responsible for the observed organic matter levels, since this favors production of plant material more than microbiological decomposition processes. This appears to be the most plausible explanation so far advanced to account for organic matter accumulation in tropical soils.

2. *With Respect to Horizon within the Profile*

The quantity and nature of organic matter occurring at various depths in soils are dependent upon a number of environmental factors. Of these the most clearly related are probably rainfall and type of vegetative cover. Where the annual addition to the soil organic fraction

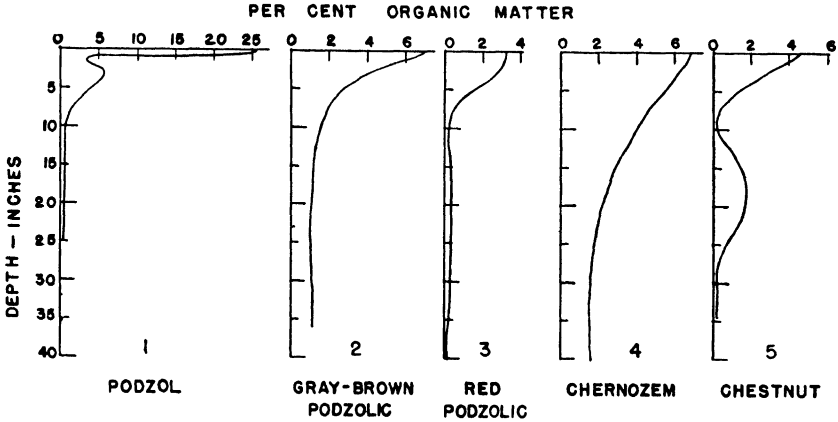

FIG. 1. Distribution of organic matter in profiles representing several great soil groups.

1. Byers *et al.* (1935) 2. Brown and Thorp (1942) 3. Byers *et al.* (1935)
4. Hopper *et al.* (1931) 5. Brown and Byers (1935)

takes the form of leaf fall the layers of accumulation are at and near the surface, with a very sharp decrease below the shallow surface layer, indicating that downward movement is slight. Such compounds as are sufficiently soluble to be leached down the profile in humid region soils may also be readily assimilated by soil organisms and decomposed, and on this account do not accumulate to any extent. On the other hand, under grassland vegetation most of the subsoil organic matter is formed

in place from root residues. In consequence organic matter in quantity is found at greater depths and the rate of decrease down the profile is gradual. Figure 1, taken from the data of several investigators, shows the organic matter distribution in a number of soil profiles. The data used in the figure were obtained from carbon contents and use of a single conversion factor, and on that account do not give an entirely accurate estimate of the vertical distribution of total organic matter, since the carbon content of the organic fraction usually decreases with increasing depth; however, they are useful for purposes of comparison.

The work of Jenny (1941) dealing with the effect of rainfall on nitrogen-depth relations demonstrated that the greater production of vegetation in moist climates is reflected through the entire profile.

IV. Composition

1. *Polysaccharides*

As precursors of soil organic matter, the constituents of plant tissue may be divided into three general groups which together comprise the major portion of mature plants: (1) polysaccharides, (2) lignin, and (3) protein. Of these the polysaccharides are by far the most abundant, cellulose alone usually amounting to about half the dry weight of tissue. The other major polysaccharides are the hemicelluloses, including polyuronides. Norman (1931, 1933) has shown that the hemicelluloses suffer very early and extensive loss during microbial decomposition, followed by increasingly rapid removal of cellulose. After the initial stages in decomposition most of the weight loss is due to breakdown of cellulose. On the basis of their susceptibility to microbial attack, the principal structural polysaccharides of plants are therefore not likely to accumulate in soils. It is difficult to estimate how much of the organic fraction in soils consists of cellulose, hemicelluloses, and simpler polysaccharides since suitable analytical methods are not available for the purpose. Waksman and Stevens (1930) applied to soil systems a proximate method of analysis which had been used a great deal in the study of plant residue decomposition and obtained figures of the order of 10 per cent of total organic matter as polysaccharides. By applying this type of analysis to some of the soils of northeast Scotland, Forsyth (1948) obtained figures of the order of 0–5 per cent cellulose, 5–20 per cent hemicelluloses, and 5–15 per cent uronic anyhydride. Although the fractions determined by these empirical methods undoubtedly do not give a good separation of components, it is obvious that soil organic matter differs considerably from plant material with respect to polysaccharides.

In view of the susceptibility to decomposition of the major polysaccharide constituents of plants, which appear to function chiefly as an energy source for microorganisms, Forsyth (1948) believes that any direct contribution of plants to soil polysaccharides must come through the polyuronide hemicelluloses.

The characterization of soil polysaccharides is far from complete, but it appears that the polyuronides occupy an important position among them. Uronic acid units apparently are less susceptible to decomposition than are pentosans and hexosans associated with them in the hemicellulose group, as shown by Waksman and Reuszer (1932). Norman and Bartholomew (1943) observed that 10–15 per cent of the organic carbon of surface soils they analyzed was present in uronide groupings and that the proportion of uronic to total carbon increased with depth. Why these sugar acids should accumulate in soil is not clear, since polyuronide gums are readily subject to microbial attack (Norman and Bartholomew, 1940). These workers suggested that uronic acids are stabilized by combination with some other grouping to give a resistant complex. It may well be that the situation is analogous to the accumulation of organic nitrogen compounds in soil, which are not only stabilized by association with clays, possibly with lignin, but are also continually being synthesized in microbial tissue. Fuller (1946, 1947) has adduced evidence of the microbial origin of soil uronides, although this is indirect, since it is based on similarities between decarboxylation rate curves of soil organic matter and bacterial gums.

Estimates of the quantity of uronic carbon in soils have been criticized by Bremner (1950a) in a recent review on grounds that the method of determination is not specific for the uronic carboxyl grouping, giving results which he considers to be impossibly high. His contention is that the conventional method, involving prolonged boiling with 12 per cent hydrochloric acid, splits off carboxyl groups of nonuronic origin, although these do not interfere seriously when the method is applied to plant materials. The objections raised by Bremner should be considered in any attempt to assess the quantitative importance of uronic acids in soils, but on the other hand, the accumulation of data indicating the presence of relatively large amounts of uronides cannot be overlooked. One piece of circumstantial evidence which has not been emphasized previously is the fact that the carbon content of organic matter decreases with depth, whereas the uronide content increases. Since the carbon content of the organic matter of most surface soils is in the vicinity of 50–52 per cent, whereas that of pure uronide is 40.9 per cent, an increase in the proportion of uronide would lower the carbon content of the organic fraction. Coupled with this is the fact that the exchange capacity of

organic matter also increases with depth, indicating the presence of more acidic groups.

Forsyth (1948, 1950) and Stevenson *et al.* (1952) have been able to isolate and identify uronic acids in the hydrolyzates of soil organic matter extracts by means of paper chromatography, thus providing unequivocal evidence of their presence. Forsyth (1950) determined the constituent sugar units in two soluble polysaccharides obtained from a "fulvic" fraction representing 1–2 per cent of the total organic matter. Of these polysaccharides 15.8 and 16.9 per cent, respectively, were present as uronic anhydride, which would account for 0.15–0.34 per cent of the soil organic fraction. However, Forsyth regarded his yields as minimal.

The positive identification of uronides in soil organic matter, together with the isolation by Forsyth and Webley (1949) of a considerable number of soil bacteria capable of synthesizing polysaccharides containing uronic acid units, gives further support to the belief that this group constitutes an important fraction in soil.

The carbohydrate content of soil microorganisms is subject to considerable variation, depending on the age of the cells, the amount and nature of available substrate, and other factors. Cellulose appears not to be a major structural constituent, although its presence has been demonstrated in the cell wall of a few bacteria of the acetic acid group (Brown, 1886; Beijerinck, 1898) and in several species of fungi (DeBary, 1887; Mangin, 1899; Thomas, 1928). Chitin, a polymer of N-acetylglucosamine which is analogous to cellulose in many respects, is a structural component of many of the filamentous fungi. Schmidt (1936) isolated chitin from fifteen species of fungi in yields up to 4 per cent of the dry weight of mycelial tissue. Norman and Peterson (1932) reported a nitrogen content of only 3 per cent in the alkali-resistant fraction of *Aspergillus fisherii* as compared with 6.9 per cent in pure chitin, which would indicate the presence of other polysaccharides linked to chitin or occurring as infiltrating substances in the structural fabric. The presence of amino sugars in soil, observed by Bremner (1949a), confirms the occurrence of chitin or its degradation products.

A large number of microorganisms have the capacity to synthesize polysaccharides, the formation of which may be endocellular, capsular, or exocellular, and frequently may be a major metabolic product, according to Evans and Hibbert (1946). Forsyth and Webley (1949) found that bacteria capable of polysaccharide synthesis were present in various agricultural, moorland, and forest soils, and estimated that these may form 5–16 per cent of the viable bacterial population. Chemical examination of the polysaccharides produced distinguished four types,

in three of which uronic acids occurred in combination with other types of sugar units, presumably in the form of mixed polymers. Fungal polysaccharides have not been extensively studied, but it is probable that they contribute substantially to the soil organic fraction in view of their known synthetic abilities and of the considerable proportion of fungal tissue in relation to other forms. A piece of fungal mycelium 5μ in diameter and 1 cm. long would be roughly equivalent in weight to a million small bacteria of the type found in the indigenous soil population.

2. *Lignin-Derived Fraction*

In the decomposition of plant residues in soil, cellulose and hemicelluloses are readily utilized by a wide variety of soil microorganisms as a source of energy, whereas lignin is broken down only slowly. As a consequence the relative proportion of lignin in the residue increases; this fact is one of the chief supports for the belief that a large proportion of soil organic matter is either lignin or lignin-derived. Further support is provided by the presence in soil of a fraction which, like lignin, may be dissolved in alkali and subsequently precipitated by the addition of excess acid, is resistant to hydrolysis by strong mineral acid, contains methoxyl and phenolic hydroxyl groups, and is attacked by relatively mild oxidizing agents. Gottlieb and Hendricks (1945) attempted to obtain more direct evidence of a lignin fraction in soil organic matter through the application of alkaline nitrobenzene oxidation and high-pressure hydrogenation, techniques which have been very helpful in elucidating the structure of wood lignin. They were unable to isolate definitely characterizable products from soil organic matter preparations, in contrast to the situation with wood lignin, from which propyl benzene derivatives can be obtained in good yield. This indicated drastic alterations in plant lignin during the course of decomposition in soil. On the basis of similarities between alkali lignin and soil organic matter preparations in their behavior toward hydrogenolysis, these workers hypothesized a condensation of demethoxylated lignin molecules with the production of fused ring structures. In relation to this point it may be noted that Scheffer and Welte (1950) observed marked similarities in the ultraviolet absorption spectra of alkali lignin from several sources and soil humic acid preparations.

In addition to the probable conjugation of ring structures in lignin during decomposition, there is ample evidence of other changes in the molecule which differentiate the lignin-derived fraction in soil from the unaltered constituent in plants. Methyl groups are split off, as shown by decrease in methoxyl content (Waksman and Smith, 1934). Cation

exchange capacity increases (Millar *et al.*, 1936; Bartlett, 1939), probably owing to oxidation of side chains to carboxyl and exposure of phenolic hydroxyl groups by demethylation.

Unlike the polysaccharides, lignin is not synthesized by soil bacteria, but Thom and Phillips (1932) have reported the presence in fungi of large amounts of a fraction resembling lignin in its resistance to strong acid hydrolysis. This fraction, varying from 2.65 to 54.08 per cent in the species they analyzed, differs from lignin in higher plants in that the methoxyl content is negligible. However, this does not exclude the possibility that the fungal constituent is structurally similar to lignin. More recently Pinck and Allison (1944) reported synthesis of ligninlike complexes by several species of fungi.

It appears, then, that the resistant portion of soil organic matter is somewhat unlike lignin, though resembling it in several respects. The carbon content alone serves to give an indication of this, since wood lignin usually contains more than 60 per cent, whereas organic matter of surface soils rarely contains more than 52 per cent, and the value may be much less in subsurface layers. A fresh approach is needed in which the microbial origin of a large part of the soil organic fraction is given full consideration. This is not to say that techniques and methods developed in the study of plant lignin need be rejected, although past experience indicates that these frequently cannot be used without modification. Rather this is an argument that the field of microbial chemistry is one to which soil scientists might profitably give more attention. The extrapolation of plant chemistry to cover this field has been useful in organic matter research, but interpolation between the properties of plants and of microorganisms might come closer to the true situation.

3. *Organic Nitrogen Fraction*

Nitrogen accounts for something like 5 per cent of soil organic matter and must occur as an integral part of many of the compounds present, since it is extremely difficult to obtain any sort of soil extract free from nitrogen. It occurs in fairly constant proportions in the organic matter of soils of very diverse character; indeed, Read and Ridgell (1922) found the nitrogen content to be more constant than that of carbon. Much of the organic nitrogen is unquestionably protein-derived since proteins are present in plant residues and microbial protoplasm, although adequate experimental verification for this inference has been obtained only recently. Kojima (1947a, b) was able to account for 37 per cent of the total nitrogen in a muck soil as alpha-amino nitrogen and isolated several common amino acids in good yield. However, she concluded that not more than 66–75 per cent of the organic nitrogen could be consid-

ered as protein. Comparative uniformity in amino acid composition was indicated by the work of Bremner (1950b), who found the same twenty amino acids in hydrolyzates of six soils. No free amino acids were detected before hydrolysis. Bremner (1949a) considered one-third of the total nitrogen in soils in proteinlike combination to be a minimal figure. If generalization may be permitted on the basis of the work cited, roughly between one-third and two-thirds of the soil organic nitrogen occurs in the protein-derived fraction. Information concerning the manner of combination of the remainder is very meager, but some of it occurs in heterocyclic ring compounds such as the purines and pyrimidines. Bremner (1951) estimates that not more than 10 per cent of soil nitrogen occurs as nucleic acids. Nitrogen containing rings must also form a part of the fused ring structures of the lignin-derived fraction. Flaig (1950) has suggested the similarity to soil humic acids of melanin, which appears to form a chain structure through conjugation of 5, 6-dioxyindole rings. The presence of glucosamine in soil hydrolyzates indicates that part of the nitrogen is present in the carbohydrate fraction.

The question of a ligno-protein complex in soil has not yet been resolved, but so far the evidence in support of the existence of such a complex is only presumptive at best. The idea was advanced to account for the apparent resistance of soil nitrogen to microbial decomposition, since free proteins are readily attacked. In view of the accumulation of lignin due to its relatively unreactive character, it seemed reasonable to postulate a masking effect of resistant lignin upon easily decomposed protein. Certain superficial similarities were observed between a synthetic ligno-protein (Waksman and Iyer, 1932) and soil humus. The postulated mechanism of combination does not adequately explain the resistance to microbial attack, as pointed out by Norman (1942), nor the reactivity toward hydrogen peroxide of soil organic matter (McLean, 1931). Alternative explanations have been offered by Ensminger and Gieseking (1939, 1942), who found proteolysis to be inhibited in the presence of clays, and by Broadbent and Norman (1946), who obtained evidence that some of the soil organic nitrogen is quite readily mineralized. In view of the evidence that the acid-resistant fraction in soils is unlike plant lignin in many of its properties and that a large portion, perhaps more than half in some cases, of the soil nitrogen is of nonprotein nature, it would seem that the lignin–protein idea in its original form is now obsolete. Mattson and Koutler-Andersson (1943) suggest that some of the stable nitrogen compounds in soil might be produced by interaction of oxidized lignins and ammonia or possibly aromatic amines at the sites of phenolic hydroxyl groups to form amidophenols,

which upon oxidation and condensation would form a polymer containing ring nitrogen. The proposed reaction seems tenable and is partially substantiated by the finding of Bennett (1949) that when hydroxyl groups in oxidized lignin were blocked by methylation, very little nitrogen was assimilated into the molecule upon treatment with ammonia, whereas more than 7 per cent nitrogen could be "fixed" by an oxidized commercial lignin.

4. *Fractions Obtained by Empirical Fractionation Procedures*

One of the properties of soil organic matter which makes its characterization difficult is its inherent insolubility. No solvent is known which dissolves the complex completely. Strong alkali brings a considerable part of the material into solution and on that account has been used extensively in research dealing with so-called humic and fulvic acids, which are, respectively, the precipitate and filtrate resulting from the addition of excess acid to an alkali extract. All extractants with an alkaline reaction suffer the disadvantage that the material is concurrently oxidized and probably altered in other ways, so that the preparations thereby obtained are to some extent artefacts of the method.

A procedure popular in Germany divides soil organic matter into two fractions, depending on solubility or insolubility in acetyl bromide. However, Springer (1943) and Siegel (1941) reported inability to obtain clear relationships between the relative amounts of organic material insoluble in this reagent, presumed to be the true humus, and other soil properties. Other separations have been based on peptization in sodium chloride (Sowden and Atkinson, 1949) and on density (Henin and Turc, 1950), but whether these represent an improvement over other empirical methods has not yet been clearly demonstrated.

In an attempt to get away from the difficulties of the classical extraction with strong alkali and the attendant drastic effect on soil organic matter, Bremner and Lees (1949) investigated the extracting ability of a number of inorganic and organic salts of sodium. Of these the pyrophosphate proved to be the most satisfactory, having an extracting efficiency in tenth-molar solution comparable to that of fifth-molar sodium carbonate. The chief disadvantage of this reagent appears to be that it removes only a small proportion of the total organic matter, on the order of 10 per cent in three of the four soils Bremner and Lees investigated, though the percentage was somewhat higher in the fourth. However, the more drastic extraction by strong alkali is by no means complete, so that the advantage of obtaining relatively unchanged material through the use of pyrophosphate probably outweighs the disadvantages of low yield and selective solution. Neutral extractants will probably

be used more extensively in future organic matter research. Stevenson *et al.* (1952) have recently used the pyrophosphate extract to advantage in attempting to characterize organic matter occurring in intimate association with clay. Electrophoretic examination of the extract indicated that it consisted mainly of a single colloidal component, although supporting chemical data showed that its constitution was complex. Several amino acids and sugars were identified in hydrolyzates of the extract.

V. Physicochemical Properties

1. *Resistance to Decomposition*

The soil organic fraction has been widely regarded as the end product of a series of decomposition reactions which produce a material chemically and biologically stable. This property has been ascribed to the presence of lignin, which is not only relatively inert itself but confers stability upon other plant constituents with which it is closely associated in natural materials. For example, in the work of Olson *et al.* (1937) the rate of cellulose decomposition was shown to be related to the lignin content of several partially delignified materials. Since the organic matter level of cultivated soils receiving sizable annual increments of plant residues usually reaches an equilibrium value lower than that in the virgin state, it is obvious that decomposition must be going on at a fairly rapid rate and that added residues are almost completely decomposed each year, or an equivalent amount of the soil organic fraction is lost. Actually neither process occurs to the exclusion of the other, but in the past the loss has been attributed almost entirely to the added residues or green manure. Through the use of the C^{13} tracer, Broadbent and Norman (1946) showed that decomposition of the soil organic fraction is accelerated during the flare-up in microbial activity accompanying the addition of fresh residues. Some of the added material accrues to the soil organic fraction, and at equilibrium an equivalent amount of the latter is decomposed. These findings have been substantiated by Hallam and Bartholomew (1953), whose experiments, involving three soils and two plant materials, showed that the stimulating effect of added residues persisted for more than a hundred days. In all cases the native organic matter was more extensively decomposed when additions of plant material were made. This may not be the case when the quantity of added residues is small compared to the total quantity of organic matter, as suggested by the results of Bingeman *et al.* (1953). In their experiments with an organic soil the so-called "priming" effect lasted only a short time. Pinck and Allison (1951), though not using isotopic tracers

in their investigations, concluded that the effect of green manure on the biological oxidation of soil organic matter was of only minor practical importance, since only 2–3 per cent of the total organic matter was concerned. Figure 2, calculated from the data of Broadbent and Bartholomew (1948), shows the relative rates of decomposition of the soil organic fraction alone and in the presence of Sudan grass added to it.

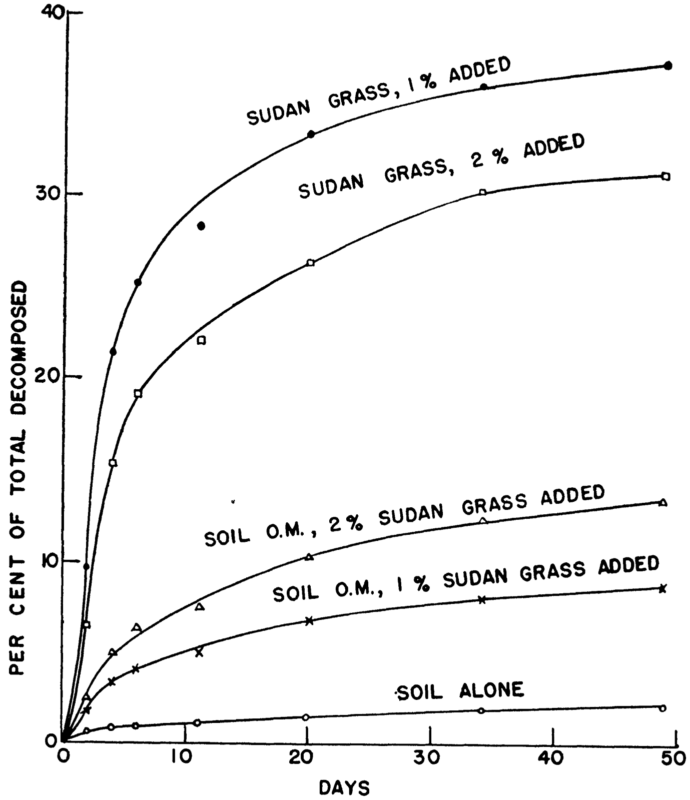

FIG. 2. Relative decomposition rates of soil organic fraction and of Sudan grass added to it.

The addition of 1 per cent Sudan grass resulted in the decomposition of 8.8 per cent of the soil organic matter during a forty-nine-day period as compared with 2.2 per cent in the soil alone. During the same period 37.5 per cent of the grass was lost. On an acre basis this would correspond to the loss of 1030 pounds of soil carbon, which could be just compensated by the addition of 6870 pounds of Sudan grass. There would be 70–90 pounds of nitrogen and perhaps 8–10 pounds of phos-

phorus in the organic matter decomposed, which would be mineralized, provided the added residues were not deficient in these elements from the standpoint of microbial requirements.

2. Chemical Oxidation

In addition to the breakdown of soil organic matter by microorganisms, another oxidative process of a strictly chemical nature has been shown to occur. This involves direct absorption of atmospheric oxygen in the presence of alkali. According to Bremner (1950a), this uptake of oxygen continues for a long time and is affected by the nature of the soil and the concentration of alkali. The mechanism of the reaction is

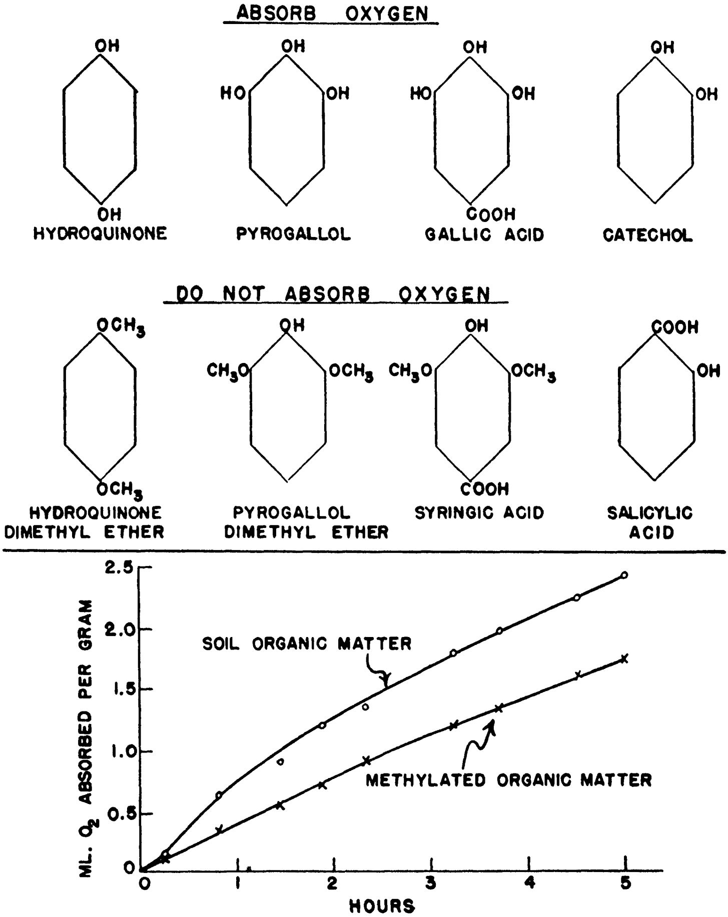

FIG. 3. Illustration of the relation between substituent groupings and the ability of several substances to absorb oxygen in alkaline solution.

not understood but appears to be related to the presence of at least two hydroxyl groups on an aromatic nucleus, as shown in Fig. 3. Replacement of hydroxyl hydrogen by methyl in simple compounds of the type shown destroys the ability to absorb oxygen readily. Methylation of soil organic matter preparations decreases the rate at which they absorb oxygen in alkaline medium but does not entirely eliminate this property. Among the large number of degradation products which could be formed by oxygen absorption are the quinones. Evidence of quinone structures in soil was obtained by Feustel and Byers (1936), who were able to obtain yields of tetrabromoquinone of the order of 10 per cent from brominated peat and soil humic acid preparations. Flaig (1950) has attributed a quinoid structure to humic acids. It is quite clear, however, that oxidation may proceed past the quinone stage, since Bremner (1950a) reports that 1–4 per cent of the organic carbon in soil may appear as carbon dioxide in a few days.

The practical importance of chemical oxidation of organic matter has not been investigated, but it undoubtedly occurs in soils of strongly alkaline reaction and may be responsible for the black color of certain alkali soils. Forsyth (1947) suggested that the dark color of humic acid preparations is due to oxidized quinones, since he was able to obtain pale yellow solutions by reduction with sodium amalgam in an atmosphere of nitrogen. When exposed to air, the solutions darkened again.

3. *Cation Exchange*

It is well known that organic soils and organic matter preparations from mineral soils possess exchange capacities which on a weight basis are very high relative to those of clays. It is also known that the capacity of decomposing plant materials to retain bases increases as decomposition progresses, indicating the formation or exposure of reactive groupings. The obvious inference is that organic matter accounts for an appreciable part of the total cation exchange capacity in soils, and in fact it has been repeatedly demonstrated that destruction of the organic fraction with hydrogen peroxide produces a decrease in exchange capacity. This decrease has been commonly used to estimate the contribution of the organic fraction to total exchange capacity. This method is unsatisfactory for two reasons, the first of which is that organic matter is not completely destroyed by the peroxide treatment. Kelley and Thomas (1942) subjected ten representative Maryland soils to the peroxide treatment and found that in none of the soils was more than 75 per cent of the organic matter destroyed and that the average was about 60 per cent. The second fault of the peroxide method is that partial destruction of the organic fraction apparently unmasks some of the exchange

sites which are blocked through interaction between organic matter and clay. Myers (1937) attributed the reduction in the exchange capacity of organic-inorganic systems resulting from mixing the two components to steric hindrance rather than to chemical union. Just what proportion of the cation exchange groupings are blocked by this sort of interaction under natural soil conditions is unknown, but it seems unlikely that only the organic sites are blocked, as McLean (1952) has suggested recently.

Estimates of the contribution of the soil organic fraction to the total exchange capacity of soils obtained by existing methods are only approximate, but there is no doubt that it is usually quite large. Bartlett *et al.* (1937) found that the loss of exchange capacity due to hydrogen peroxide treatment of a large number of Maryland soils varied a great deal but in some cases was as high as 90 per cent. Kelley and Thomas (1942) reported comparable figures of 50–80 per cent in Maryland soils; Olson and Bray (1938) found that organic matter accounted for 7–43 per cent of the exchange capacity in several Illinois soils. They stated that there has been a tendency to overemphasize the inorganic complex in base exchange studies. As would be expected, a large part of the exchange capacity in peats and mucks and in sandy mineral soils lies in the organic fraction. McGeorge (1930) obtained a linear correlation between total exchange capacity and carbon content in a group of twenty-one soils, most of which were organic. The slope of his regression line was 2.9 meq. per unit per cent carbon, corresponding to an exchange capacity of about 159 meq. per 100 g. organic matter. Calculation of a similar figure from Chandler's (1939) data on forest soils of the Adirondack region gives a value of 186 meq. per 100 g. loss-on-ignition. Since the clay content of these soils was very low, Chandler considered the loss-on-ignition to be a good estimate of organic content. These values are low compared to the 508 meq. obtained by dividing the organic exchange capacity by soil organic content in the data of Kelley and Thomas (1942). It is unlikely that a single factor can be obtained which will permit an accurate estimate of the organic exchange capacity from the content of organic carbon in soils of diverse character, although a fairly good inverse relationship may be found between organic exchange capacity and per cent carbon in the organic fraction. The reason for this is that when carbon is low the proportion of oxygen is likely to be correspondingly high, indicating the presence of oxygen-containing groupings such as carboxyl which can function in cation exchange. Since the carbon content of the organic fraction usually decreases with increasing depth, subsoil organic matter is relatively more active in cation exchange than that of surface soils, as is shown by the data of Barshad and Rojas-Cruz (1950) in Table I. Unless these facts are taken into consideration,

TABLE I

Organic Matter and Cation Exchange Properties of an Equatorial Podzol (From Barshad and Rojas-Cruz, 1950)

Depth Inches	Carbon, %	Organic matter by ignition, %	Carbon in O.M., %	Cation exchange capacity whole soil, meq./100 g.	Exchange capacity due to O.M., %
0–18	11.45	21.8	52.5	50.0	87.0
18–32	6.09	13.1	46.5	45.8	60.8
32–45	4.33	9.7	44.7	41.4	54.2
45–56	2.84	6.6	43.0	31.0	52.3
56–60	5.02	12.4	40.5	42.3	56.3
60–80	1.64	4.0	41.4	21.8	40.0

the effect of subsurface organic matter on the chemical and physical properties of the lower horizons is likely to be underestimated. If we take an example from the data just cited, in the lower A_2 horizon of an equatorial Podzol studied by these investigators a white, strongly bleached layer between 45 and 56 inches contained 6.6 per cent organic matter, notwithstanding the soil color. This organic matter had a carbon content of 43 per cent and an exchange capacity of 366 meq., accounting for 52 per cent of the total. If the organic matter content of the bleached layer had been calculated by use of the conventional factor it would have been estimated at 4.95 per cent, and if the further assumption were made that the exchange capacity was the same as in the surface organic matter, only 38 per cent of the exchange capacity would be attributed to the organic fraction. It is only reasonable to expect that organic acids which leach down the profile have relatively high cation retention capacities.

The groupings in soil organic matter capable of furnishing hydrogen sufficiently acidic to exchange with other cations are carboxyl, phenolic and enolic hydroxyl, imide, and possibly one or two others. Gillam (1940) inferred the presence of the carboxyl grouping in humic acid preparations from the shape of potentiometric titration curves and showed that exchange capacity could be reduced by blocking hydroxyl groups. Broadbent and Bradford (1952) were able to destroy the exchange capacity of several organic matter preparations by methylation of carboxyl, hydroxyl, and imide groups, indicating that these are the principal ones involved. Their work suggests that uronic carboxyl groups may account for a considerable part of the organic exchange capacity. Further work on functional groups in the soil organic fraction

is needed, not only in relation to cation exchange, but also from the standpoint of the next topic in this review, reaction with inorganic soil colloids.

4. *Interaction with Clay Minerals*

The ability of the soil organic fraction to combine with clays to form complexes has aroused considerable attention among soil researchers in recent years. In a general way the approaches to the problem fall into two categories. The first of these is that of the physical chemist and deals with the interaction between clays and pure organic compounds, usually alcohols or amines, the nature of the forces binding the components together, the alterations produced in interlayer spacing of the clay minerals, and so on. This work has been reviewed recently by Gieseking (1949). The second approach places emphasis on the modification in properties of the organic component as a result of reaction with clay, particularly the resistance to enzymatic hydrolysis. Early work in this field by Ensminger and Gieseking (1939) showed that the protein albumen and gelatin are adsorbed within the characteristic expansible portion of the montmorillonite crystal lattice. They later (1942) found that albumen and hemoglobin were rendered somewhat more resistant to proteolytic hydrolysis when adsorbed by expanding-lattice type of clays. The degree of interference of the clay with enzymatic hydrolysis appeared to be influenced by the exchange capacity of the clay. Bartholomew and Goring (1948) observed that phosphorus mineralization from microbial tissue was retarded in the presence of clay and that clay critically interfered with the extraction and analysis of several groups of organic phosphorus compounds. This work was extended by Goring and Bartholomew (1949, 1950), who reported that kaolinite was not nearly as effective as bentonite in reducing mineralization of organic phosphorus. They found several carbohydrate phosphates to be adsorbed by clay minerals and suggested that their susceptibility to microbial degration was thereby reduced. The fixation of carbohydrate phosphates by clay minerals was found to depend on the nature of the compound, the type of clay mineral, and the pH value of the system. Further evidence of the inhibition of dephosphorylating enzyme activity has been published by Mortland and Gieseking (1952), whose data led them to believe that the inhibition is due to the effect of the clay on the enzyme and not to adsorption of the organic phosphorus compounds. In view of the protein nature of enzymes and the demonstrated adsorption of proteins by clays, it is quite probable that enzyme deactivation by clays occurs, but it is unlikely that adsorption of the compounds subject to enzyme attack can be discounted as an important factor. The glycerophosphate used in the experiment upon which Mortland and Gieseking

(1952) based their conclusion is less strongly adsorbed by bentonite than are other organic compounds such as phytin and derivatives, as shown by Goring and Bartholomew (1950).

The effect of clays in decreasing the decomposition rate of several organic materials has been demonstrated by Allison *et al.* (1949), who observed that bentonite affected carbon retention more than did kaolinite. These workers discount the importance of aeration as a factor in the accumulation of organic matter in heavy clay soils and place emphasis on the protective action of the clay.

5. *Influence on Structure*

In recent years considerable attention has been focused on the role of organic materials in the formation and stabilization of soil structure. The advent of synthetic organic chemicals as soil conditioners will no doubt lend impetus to research in this general field. These chemicals, some of which appear able to modify soil structure very rapidly, may simulate the compounds in soils which require much longer periods of time to produce measurable results. The possibility of certain structural similarities may provide valuable clues in the search for what might be termed the active constituents of the soil organic fraction from the standpoint of their effect on structure. The entire problem of soil structure is an extremely knotty one, and its relationships to properties which can be measured in the laboratory as well as to plant growth are complex. Simple explanations for the complicated phenomena associated with the condition of good tilth in soils are not likely to prove adequate, but at the present time it seems quite certain that the role of microorganisms and of nonliving organic matter is an important one.

Myers (1937) studied the physicochemical relations between organic and inorganic soil colloids as related to the formation of stable aggregates and observed modifications in properties resulting from physical admixture. His results indicated that the favorable effect of organic matter on the formation of water-stable aggregates was due to irreversible drying of the organic colloid rather than flocculation of the clay colloid, since water-stable aggregates apparently would not form without desiccation. This work differs from much of that subsequently performed by other investigators in that the organic materials were not allowed to decompose after mixture of the colloids, so that any immediate effect of living microorganisms was excluded. The decomposition process appears to be important, as has been demonstrated by several workers. When a soluble compound such as sucrose is added to soil, no immediate effect on aggregation is observed; incubation, on the other hand, produces a marked increase in water-stable aggregates (Peele,

1940). The increase in aggregation produced by such compounds passes through an early maximum during the course of incubation and falls off thereafter, indicating that the microbial products causing the aggregation are subsequently decomposed, at least in part. A twofold effect of added organic matter on soil aggregation has been pointed out by McHenry and Russell (1944), who observed that undecomposed organic matter mixed with sand and clay in increasing amounts had a diminishing effect on the amount of aggregation, apparently owing simply to the dilution effect. They concluded that organic matter supplies orientation centers for the formation of aggregates and upon decomposition furnishes microbially produced slimes and mucilages which act as cementing materials. The mucilaginous capsular material produced by microorganisms usually consists mainly of polysaccharide, and on this account this class of compounds has received considerable attention in soil aggregation studies, as in the work of Martin (1945, 1946) and Geoghegan (1947). In this work it has been demonstrated that polysaccharides of microbial origin are capable of inducing an increase in water-stable aggregates, though the effect is quite ephemeral in some cases. Geoghegan (1950) noted that the aggregating effect of some microbially produced levans varied with their molecular weight: the larger the molecule, the greater the effect. This author believes that the aggregating effect is related to hydroxyl content and suggests that hydrogen bonding may be the mechanism by which polysaccharides bind soils. The possible function of substituent groupings has also been suggested by Swaby (1950), who obtained evidence that colloidal substances containing amino, carboxyl, and hydroxyl groups were partly responsible for the cementing action on clays.

At the present time there is still considerable confusion and uncertainty about clay-organic matter relationships and their bearing on soil structure. It is of course quite clear that there are many compounds produced by soil organisms which exert an aggregating effect upon soils, but the inference that these are of importance under field conditions has been perhaps too readily drawn. The production of polysaccharides in good yield by pure cultures of bacteria growing on artificial media containing an abundant source of soluble nutrients is one thing, but the process in the keenly competitive environment of the soil, in which available substrate is normally in short supply, is quite another. In order to have practical importance as an aggregating agent a substance should be active in relatively small amounts, reasonably resistant to microbial decomposition so that it can accumulate to some extent in soils, or continually produced in some quantity by the soil population. Most of the microbially produced polysaccharides are readily decomposed, so that

the effect produced upon aggregation by their addition to soils is of short duration and may have little significance under actual field conditions. The apparent resistance to decomposition of soil polyuronides suggests that they may be active aggregating agents. However Geoghegan (1950) found that the addition of pectin and alginic acid, both of which have a high polyuronide content, had little effect upon structureless soils in which the exchange complex was saturated with either calcium or sodium, but had a marked effect on hydrogen soils. This behavior is difficult to reconcile with that of synthetic polymers similar to uronic acids in the possession of carboxyl groups at intervals along the chain. In pectin the carboxyl groups are not free, most if not all of them being esterified, although enzymatic hydrolysis of the ester linkages is probably quite rapid in soils. In alginic acid, a hydrolysis product of an algal polyuronide, the carboxyl groups are not blocked.

An indication that organic substances effective in aggregation are continually synthesized may be obtained from consideration of the conditions necessary for production of the most favorable type of soil structure. In the rhizosphere of a grass sod the microbial population is very active, owing to the production of root tissues and secretions which provide them with energy material. Synthesis of microbial cells and metabolic products is thus kept near the maximum. However, microbial activity alone cannot account for the superiority and the stability of the structure associated with sod; the production of an extensive fibrous root system is undoubtedly an important factor in holding aggregates together, and the chemical composition of the root tissues is probably related to the stability of the good structure which is formed.

VI. Methods of Determination

1. *Determination of Organic Matter*

Analysis of soils for their organic content is performed so frequently as a routine test and reported so often in connection with all sorts of soil investigations that it would seem to be a very simple and easy process. Strictly speaking, however, no highly accurate method for determination of soil organic matter exists. This fact, which was pointed out by Alexander and Byers (1932) twenty years ago in an excellent critical review, is equally true at the present time. The two methods of determining organic matter *per se* involve the destruction of this component in soil, after which the loss in weight is taken as a measure of the organic content. In one of these hydrogen peroxide is used to oxidize the organic matter; as pointed out previously, the oxidation is

incomplete, and the results obtained are therefore too low. In the other method organic matter is destroyed by ignition, which results in quantitative oxidation but breaks down inorganic constituents as well. This method, which is of no value when applied to most soils, seems to be suitable for approximate analyses on highly organic soils and on those in which the inorganic colloid content is very low. Moreover, it provides the basis for the most accurate method available, namely, that proposed by Rather (1917) and modified by Alexander and Byers (1932). In the Rather method the soil is pretreated with a mixture of hydrochloric and hydrofluoric acids, which effects removal of the hydrated mineral matter; loss on ignition then gives a valid estimate of organic content. However, the pretreatment dissolves a small part of the organic material and is quite time-consuming, which makes the method unsuitable for routine work.

2. *Determination of Organic Carbon*

A number of methods for determination of soil carbon are available, and in fact carbon is determined in the majority of the so-called organic matter analyses. The classical dry-combustion method gives excellent results and when suitably modified is fairly rapid. Some of the wet-combustion procedures give results which compare very favorably with it. In particular the methods of Van Slyke and Folch (1940) and of Plice and Lunin (1941) might be mentioned. It is significant that in both of these methods the organic matter is oxidized quantitatively to carbon dioxide and the carbon dioxide is determined directly. In most of the other wet-combustion procedures the oxidation is not quantitative, and the extent of reduction of the oxidant is taken as the measure of carbon present. Methods which are neither quantitative nor direct suffer obvious disadvantages when a high degree of accuracy is desired, but these are offset by time considerations in much routine work. It is not the purpose of this review to discuss in detail the relative merits of the various rapid methods currently in use.

Customarily organic matter content is calculated from the carbon figure by use of a factor, and it is in the use of this factor that difficulty arises. The carbon content of the soil organic fraction varies from one soil to another and in particular with depth in the profile. The use of the usual conversion factor 1.724, which has become established through long use rather than adequate experimental verification, may lead to an error as large as 50 per cent in estimating subsoil organic matter. Figure 4 is a histogram showing distribution of the carbon to organic matter conversion factor among sixty-three samples of surface soils taken from the data of Read and Ridgell (1922), Alexander and Byers (1932), and

Broadbent (unpublished). The conventional value is clearly too low in the great majority of cases; it is also apparent that the distribution is skewed toward the higher values, indicating that use of a modal factor might frequently lead to serious error. The ideal situation would be to determine the factor for each soil. As a practical matter, it would be much better to report carbon rather than organic matter when carbon is determined. If a factor is to be used, values of about 1.9 for surface soils and about 2.5 for subsoils are more satisfactory than 1.7. It might

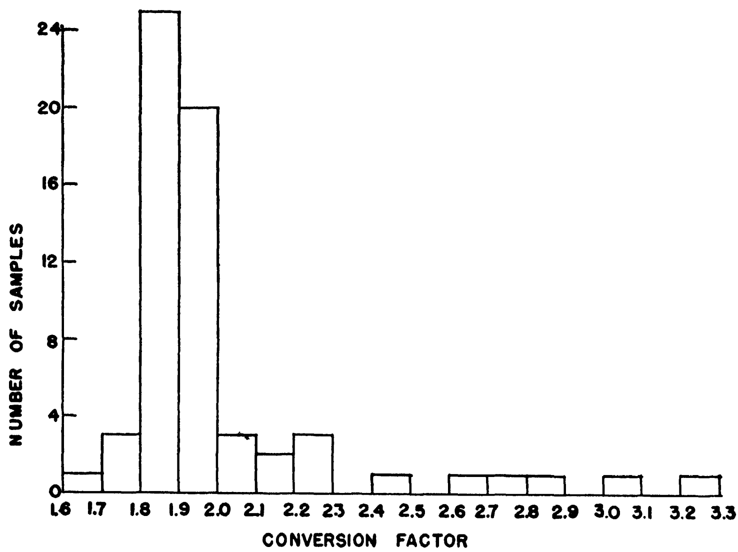

FIG. 4. Frequency distribution of factor for converting organic carbon to organic matter in 63 surface soils (from Read and Ridgell, 1922; Alexander and Byers, 1932; and Broadbent, unpublished data).

be argued that a knowledge of the carbon content provides just as much information as the total organic matter, and this is probably true for surface soils of similar character. However, when comparisons are made between dissimilar soils or between horizons within a profile this is less likely to be the case.

VII. Contribution to Plant Nutrition

The soil organic fraction affects fertility indirectly in many ways, but also has a very important direct function as a reserve of certain plant nutrients which become available through the activity of the microbial population.

1. *Nitrogen*

Nitrogen occupies a unique position among the nutrient elements in that it occurs almost entirely in the organic form in soils. Since the supply of available nitrogen is very closely related to crop yields, the factors governing the conversion of the organic reserve to the available form are of great importance. The soil organic fraction furnishes the raw material for many of the important processes in the nitrogen cycle and provides the fuel for most of the microbial transformations involved. This close relationship between the carbon and nitrogen cycles makes it possible to relate certain nitrogen transformations to the carbon: nitrogen ratio. Thus, when the ratio is large, an unbalance exists in the proportion of energy material available to the soil population to the quantity of nitrogen which can be used for synthesis of new cells. Under these conditions no net increase in inorganic nitrogen can occur; in fact any available nitrogen present is rapidly assimilated by microorganisms. The well-known nitrate depression which follows plowing under large quantities of wheat straw or stubble is a typical example of the situation just described. Nitrogen mineralization does not occur until the unbalance has swung over to an excess of nitrogen, corresponding to a low carbon: nitrogen ratio. This is accomplished by the conversion of excess energy material to carbon dioxide and water. The ordinary circumstance in the soil organic fraction is that the carbon: nitrogen ratio is low, but the supply of readily available energy material is limited and ammonification is rather slow. This arrangement is advantageous in several respects. The main reserve of soil nitrogen is held in an insoluble form which cannot be leached away and is slowly converted to forms which can be utilized by plants. In many cases, however, mineralization is too slow to supply the current needs of a growing crop. In this apparently anomalous situation two or three thousand pounds of nitrogen may be present in an acre of soil, and yet a crop requiring perhaps 70 pounds in a season may suffer from nitrogen deficiency. The mineralization process can be speeded up by increasing the activity of the soil population; this may be accomplished through the addition of decomposable organic material, provided the nitrogen requirements of the microbial population are also met. Thus, plowing under a green manure crop stimulates microbial activity, supplies nitrogen for synthesis of microbial cells, and accelerates mineralization of soil nitrogen.

When inorganic nitrogen fertilizers are applied to a soil, some of the soluble nitrogen is assimilated by soil organisms and becomes part of the organic nitrogen fraction, although it may be subsequently mineralized. A large portion of the nitrogen is therefore derived from the soil organic

fraction, even though the soil on which it is grown may have been fertilized with green manures, farmyard manure, or inorganic nitrogen compounds.

As Ensminger and Pearson (1950) have pointed out, our knowledge of the nitrogen cycle is seriously lacking in certain respects. Most of the processes are understood in a general way and can be explained in terms of over-all changes taking place, as has just been done in the case of ammonification. More detailed information concerning specific reactions and factors controlling them is urgently needed. Provided environmental conditions are suitable for microbial activity, the controlling factor is usually the available energy supply. However, expression of the energy status in terms of carbon: nitrogen ratios is an oversimplification not justified by the great diversity of substrates and of microbial populations which occur in soils. A long step forward will have been taken when the availability of a given type of organic matter can be accurately predicted and a good estimate of cell synthesis obtained. The availability of the nitrogen in organic materials has been assessed in greenhouse pot tests, such as those conducted by Parbery and Swaby (1942) and by Rubins and Bear (1942). A procedure which places emphasis on the rate of liberation of nitrogen from the organic form in humus has been developed by Harmsen and Lindenbergh (1949). Their technique involves depletion of inorganic nitrogen reserves to a very low level by cropping the soil to be tested with a fast-growing crop, which is allowed to grow until nitrogen deficiency symptoms are manifest. The crop plants in their entirety are carefully removed, root fragments are sieved out, and the soil sample is then incubated under controlled temperature and moisture conditions. Determination of water-soluble nitrogen in the soil samples at intervals permits calculation of the rate of mineralization. Estimates of the capability of soils to supply mineral nitrogen based on incubation procedures have also been obtained by Pritchett *et al.* (1947) and Cornfield (1952). The latter author concluded that ammonia as well as nitrate accumulation should be considered in assessing mineralizable nitrogen. He found that total nitrogen may be used as a rough indicator of nitrogen availability, provided no recent additions of fertilizers or organic material have been made, whereas in the soils he studied carbon: nitrogen ratios were of no value in predicting nitrogen availability.

The chief disadvantages of tests such as have been used to estimate mineralizable nitrogen lie in their time-consuming nature and in the fact that the information obtained is usually applicable only to conditions similar to those under which the test was conducted. The situation is further complicated by differences in behavior of the soil population

between cropped and fallow soils. Clark (1949) has pointed out that nitrogen mineralization is usually less in cropped soils. Goring and Clark (1948) attributed this decrease to immobilization in the soil, owing probably to the increase in numbers of microorganisms that occurs with plant growth.

2. *Phosphorus*

The contribution of phosphorus in the soil organic fraction to plant nutrition has been the subject of intensive research in recent years. Considerable evidence has been accumulated which indicates that under some conditions a substantial part of the phosphorus taken up by a growing crop may be derived from organic forms. In many soils organic phosphorus compounds may account for more than half the total reserve (Bower, 1949). The mineralization process is not well understood but appears to be analogous to nitrogen mineralization in many respects. Thompson and Black (1949) and Kaila (1949) have obtained evidence of a relationship between carbon : phosphorus or nitrogen : phosphorus ratios and the occurrence of immobilization or phosphorus release. Kaila (1950) estimated the critical phosphorus content of natural materials at 0.2 per cent. In materials having a higher content, phosphorus in excess of microbial requirements is present, and mineralization would be expected to occur. It is sometimes pointed out in objection to the view that soil organic phosphorus supplies part of the crop needs for this element that peat soils having almost all their phosphorus in organic form frequently are deficient in available phosphorus. This objection can be met satisfactorily by Kaila's (1950) explanation that the phosphorus content of peat soils is often below the critical value and the mineralization which would follow a decrease in the carbon : phosphorus ratio is limited by a lack of available energy material. This is essentially the same situation as with nitrogen, except that the critical carbon : phosphorus ratios appear to be somewhat more variable than the corresponding carbon : nitrogen ratios.

3. *Other Elements*

As a direct source of plant nutrients other than nitrogen and phosphorus the soil organic fraction is of relatively minor importance, although evidence of organometallic complexes has been obtained by Bremner *et al.* (1946), and other nutrients are, of course, retained in exchangeable form by the organic colloids. On the other hand the availability of some nutrient elements, notably iron, manganese, and sulfur, may be profoundly influenced by organic matter and the activities of the soil population. In this connection the soil reaction and oxidation-

reduction status are of particular importance. Robinson (1930) has called attention to the changes which accompany submergence of soils. Owing to the rapid depletion of oxygen through absorption by microorganisms, reducing conditions develop quickly; combined oxygen in various chemical compounds may then be utilized with resultant alteration in chemical composition of the soil solution. Sulfates may be reduced to sulfides, and insoluble ferric and manganic compounds reduced to the relatively more soluble ferrous and manganous forms. Microbially produced carbon dioxide helps to keep in solution ions which might otherwise be precipitated as carbonates or as the more soluble bicarbonates. Toxic quantities of sulfides, iron, manganese, and aluminum may soon accumulate under the conditions described. Mann and Quastel (1946) have shown that the addition of an available substrate such as glucose to soil will cause an increase in soluble manganese under aerobic conditions; a decrease in manganous ion follows the disappearance of glucose.

Under oxidative conditions, particularly in soils of neutral or alkaline reaction, iron and manganese are oxidized to insoluble forms, and deficiency of these elements may result. Leeper and Swaby (1940) reported that microbial oxidation of manganese occurred over the pH range 4.8–8.9, with the most rapid oxidation occurring between 6.0 and 7.5. Gerretson (1937) pointed out that manganese deficiency usually occurs between the pH limits 6.5–7.8, the range in which he found the manganese oxidizers to be effective.

The activities of chemosynthetic autotrophes capable of oxidizing ferrous iron to the ferric form are well known; soil autotrophes also can convert sulfur or sulfides to sulfates. Little is known concerning the importance of such groups of organisms under field conditions, but certainly they exert some influence on nutrient availability.

The indirect effects of the organic fraction, particularly the living portion, on soil fertility have received relatively little attention and deserve much greater emphasis in future research.

VII. Conclusion

Ten years ago Norman (1942), in discussing the chemistry of soil organic matter, expressed the belief that the time was ripe for a new assault on the problems related to the fundamental nature of this important soil constituent, one which would bring our knowledge of it to a level comparable to our present knowledge of clays. Progress in the intervening decade has been hampered by a world war, but some real

advances have been made, although the number of workers in this particular field is still quite small.

The goal of a fairly complete characterization of the soil organic fraction is still far from realization, but it may confidently be expected that intensive application of new techniques already at hand, such as chromatographic and electrophoretic separation, use of isotopic tracers, and ultraviolet and infrared spectrophotometry, will greatly accelerate progress in that direction.

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Progress in Agricultural Engineering

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I. Introduction

Agricultural engineers and agronomists find many areas of mutual interest throughout the agricultural industry. Both groups have helped to establish the fact that the production per agricultural worker is di-

rectly related to the investment in farm machinery and farm power, which in turn depends upon the development of certain characteristics in crops. The widespread use of farm power and machinery in agricultural production has been one of the most significant features in the development of both American agriculture and American industry.

All developments stem from basic interests of the general public. Viewed from a national standpoint, the public's interest in the agricultural industry includes four fundamental features: first, adequate quantity of production; second, satisfactory quality of products; third, production at low cost; and fourth, the well-being of the people engaged in the industry.

II. Concept of Agricultural Engineering

It seems appropriate to review briefly the various phases of agricultural engineering. Among these are:

1. Development and application of farm power and machinery.
2. Farm buildings and rural housing.
3. Farm electrification, involving the application of electric energy as heat, light, radiation, and power.
4. Mechanical processing of farm products.
5. Engineering phases of soil and water usage, including erosion control, drainage, and irrigation.
6. Methods engineering.

Engineering may be defined, generally, as "the art and science of utilizing the forces and materials of nature for the benefit of man and the direction of man's activities toward this end." This definition implies two activities, namely, art and science. The science of engineering is based upon the pure sciences, physics, chemistry, and mathematics. This is the phase of the field which is exact and rational. The art of engineering refers to the ability to judge, estimate, and manipulate the uncertainties of engineering to a satisfactory solution of a problem. It refers to a procedure which has been found by a series of trial-and-error events, carried out in as logical a sequence as possible, to produce a desired result without a knowledge of all of the basic principles involved. It is well known that at the present time the field of agricultural engineering encompasses more uncertainties than do the more common engineering fields.

The use of basic science in research in agriculture is already very great, but there are good indications that it will continue to expand. The work of Burr (1942, 1943, 1945, 1947), Burr and Sinnott (1944), and Nelson and Burr (1946) indicates the possibility of a search for in-

creased knowledge of electrophysical, electrochemical, and biological relationships. Electrical potentials have been shown to exist between living cells. The significance of electrical energy occurring naturally in living tissue is a comparatively new but challenging field of study. Likewise, the effect of electromagnetic and electrostatic fields, electric currents, and related phenomena might be applied as environmental influences on living organisms and organic materials.

The pure science approach of the biochemist and the biophysicist can be aided and supported by agricultural engineers, who apply facts directly to agricultural problems such as production, handling, processing, and preservation of agricultural products. There are no fixed boundaries to the dimensions, energies, materials, or other physical properties or their application to agricultural production processes.

III. General Characteristics of Modern Farming

1. *Increased Power per Worker*

Farm machinery and power increase the production efficiency of the agricultural worker because they change his activity from that of producing the energy required to do the work to that of control and management. According to Schwantes (1949), in 1870 there was available for the average worker in the United States 1.6 horsepower. This increased to about 5.3 in 1920, 27.8 in 1940, and an estimated 33.6 horsepower in 1948. The number of tractors on farms in the United States more than doubled in the decade 1940–1950.

The impact of mechanized agriculture has made modern farmers less self-sufficient, and to a greater extent the operator must be concerned with the necessity of meeting annual costs of operation. Good business management is a basic requirement. The Regional Bulletin "Capital Needed To Farm in the Midwest" (1947) shows that modern farming in that region is a business which requires a capital investment ranging from $14,000 to $60,000.

2. *Comparisons of Crop Yields and Per Capita Production*

Crop and per capita production on the North American Continent in comparison with other parts of the world are reviewed by Schwantes (1949). North America produces about twice as much grain per person on a dry weight basis as our neighboring continent South America and about three times as much as the people of Asia. The average for the world is 722 pounds in comparison with 1859 pounds for North America.

The yield in terms of pounds of grain per acre on a dry weight basis, however, is almost identical with that in South America and Asia. The

comparative values are 1058, 1066, and 1064, respectively. On this basis, it is evident that whereas we North Americans have been successful in making it possible for one worker to accomplish much more than in other parts of the world, we have not been so successful in increasing the yields per acre.

3. Impact of a 20 Per Cent Increase in Total Farm Output

A summary of reports of forty-eight state committees, United States Department of Agriculture Information Bulletin 88 (1952), appraising the productive capacity of agriculture during a subsequent five-year period, indicates that a total farm output about 20 per cent greater than that of 1950 could be attained under "average" or reasonably favorable conditions. It is further estimated that about 44 per cent of the projected increased output potential exists in the South, about 41 per cent in the North Central Region, and about 5 per cent each in the Northeast, Mountain, and Pacific regions.

Production of feed and livestock would be expected to make up a major part of the increased output in all regions and 58 per cent of the increased production for the country as a whole. Food grains would represent about 15 per cent of the projected increase for the nation as a whole; fruit, truck, and vegetable crops, about 9 per cent; and cotton, about 5 per cent.

A projected increase of 20 per cent above the total farm output in 1950, without a substantial increase in the farm labor force, is estimated to require about five or six times as many cotton pickers; more than twice as many forage harvesters; 30–50 per cent more balers, power sprayers, beet harvesters, and power manure loaders; 20–25 per cent more mechanical corn pickers and combines; and about 13 per cent more milking machines and silos. These estimates do not include the need for machines to replace those discarded because of wear or obsolescence.

It is estimated that a 70 per cent increase in commercial fertilizer would be required to help produce the projected increases in yield. The estimated potential maximum yield per acre of major crops and pasture, as a percentage of the 1950 yields (adjusted), is corn, 167 per cent; sorghum for grain, 124 per cent; soybeans, 141 per cent; peanuts (picked and threshed), 183 per cent; cotton (all), 176 per cent; wheat (all), 140 per cent; rice, 120 per cent, hay (all tame), 156 per cent, rotation pasture, 197 per cent. Although these production estimates bear both theoretical and practical implications, they do show a relatively wide gap between current crop yield expectancy under prevailing practices and the yields that could result if farmers were using·the known improvements that would be profitable under reasonable economic condi-

tions. This gap presents a real challenge to agricultural research, education, and extension programs. On the other hand, the fact that the estimates indicate a practical total agricultural output of one and one-half times that of the record year 1951 is, in itself, a real tribute to agricultural research. It also is good evidence that modern American agriculture is the most dynamic the world has ever known.

Farming tomorrow must be done more scientifically, and more precisely, than it was yesterday. This means that in the future even more emphasis must be placed on increased production, improvement in quality of products, better management, better equipment, and better living conditions for farm people. Better control over the factors influencing agricultural production will continue to be the principal joint objective of agricultural engineers and agronomists.

4. *A Few Important Developments, 1900–1950*

The record of new developments during the past fifty years makes it seem almost futile to attempt to forecast developments or trends beyond the next decade. As a prelude to consideration of trends in agricultural production, it seems proper to review briefly a few of the results of our efforts to gain a more abundant life during the past fifty years. We already are taking for granted some of these relatively new developments which have exerted and still are exerting a tremendous influence on our well-being and on our pattern of life. Although the basic inventions of these developments were of earlier conception, their practical applications have come in recent times. A few of these developments are:

1. The use of power and machinery in agriculture, which has reached the point where 85 per cent of the people in the United States have been released from the task of producing food. This has made possible our great industrial development and the correspondingly great increase in service occupations.
2. Telephones and other means of direct communication, which multiply human contacts and speed up business transactions.
3. Motion pictures with sound and radio and television, which serve well for disseminating information and providing entertainment.
4. Airplanes, which are now beginning to play an important part in agricultural production.
5. Electricity, for light and power, now provided on a high percentage of the farms in the United States.
6. Mechanical refrigeration for the preservation of the perishable agricultural products.
7. Pavement on the main routes used by vehicles.

8. Hybridization in farm crops and greatly improved breeding and feeding practices in the animal enterprises.

9. Widespread use of chemical fertilizers.

10. Basic practices for use in reducing water runoff and the closely related erosion of soil.

11. Transportation of liquid fuel over long distances in pipe lines.

12. Development of water resources for irrigation.

What will be the comparable developments in the second half of the century? Is it proper to say that new developments will come as rapidly and be of more beneficial influence than those of the first half of the century? Some people are inclined to think that technological advances are far outdistancing the developments in the social structure of the world. Certainly we cannot overlook the importance of the "human factor" in considering future developments. However, there is little concrete evidence to indicate that both technological and social advances will not continue at an accelerating rate.

IV. Future Trends

1. *Farm Power*

At least two kinds of power are available on about 88 per cent of the farms in the United States, namely, mechanical power and electrical power. Although both sources of power are very useful, both have certain limitations.

a. Tractor Power. Tractors of today have too few power outlets, and as a result they frequently remain idle while the operator serves as a source of power. On the other hand, electric power can be applied to many jobs on the farm, but it is limited to an area around the meter pole approximately 400 feet in radius. Another limitation on the use of electric power furnished by rural lines is unscheduled interruption of the supply. The limitations now recognized in the two power sources for the farm indicate that a combination might be most useful. An engine-electric tractor would have numerous power outlets; it would make some of the automatic features of electric power useful on field machines; and it could serve as standby power in case of interruption of the electric service.

The electrical generator and the electrical motors required for use in an engine-electric power system present some difficult design problems, but the problems appear to be subject to reasonable solutions. The cost of such a system appears to be an unreasonable handicap until the pres-

ent investment in engine-units standing idle on idle farm machines is fully recognized.

One manufacturer has recently introduced a transport-type tractor, shown in Fig. 1, to be used interchangeably with a two-row corn picker-sheller and a grain combine. These harvesting machines are mounted and dismounted on the tractor by the aid of a hoist-frame and iron transport wheels for each of the units.

Manufacturers are now concentrating heavily on the development of hydraulic systems for use in steering, for use in mounting and dismounting implements quickly and easily, and to serve as a substitute for hand-

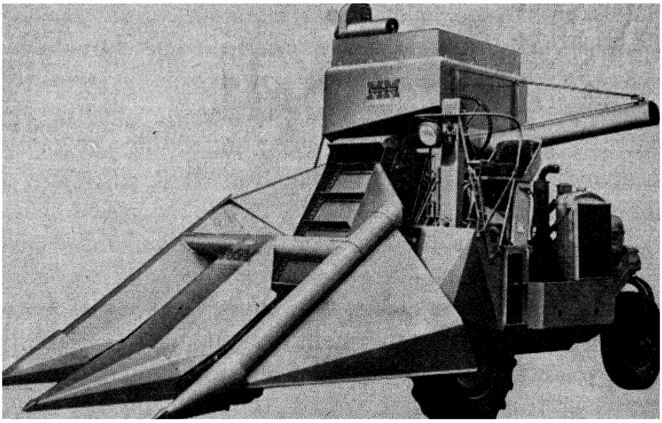

FIG. 1. A picker-sheller, mounted on a transport-type tractor. The tractor can also be used to transport a combine. The manufacturer claims that changing the attachments requires only about 30 minutes. (Courtesy of Minneapolis Moline Company.)

lever controls. In a few instances, electrical controls are combined with hydraulic control systems. In order to keep the fuel-use efficiency of the tractor engine high, some of the manufacturers are providing a means for disconnecting the drive to the hydraulic pump when it is not needed.

Methods for changing the drive-wheel spacing semiautomatically on row-crop–type tractors are being provided by a few manufacturers. Lack of good stability in the high-clearance row-crop–type tractor is causing both manufacturers and safety specialists considerable concern. Only two solutions have been proposed, first, the development of farming systems which eliminate tractor work in row crops and, second, that of easily operated devices for spreading the tractor wheels laterally so

that they will provide greater stability in the tractor while it is not being operated in row crops.

It appears that in the near furture most of the tractors will be built in compliance with the ASAE-SAE standard specifications (1944) for power take-off and drawbar hitch location and construction. Compliance with these standards makes it possible for the operator to use any make of power take-off driven machine with any make of tractor. The standards also include specifications for providing and connecting the shields along the power-shafting.

b. Electric Power. Electricity will, undoubtedly, find much greater use on American farms during the next decade. The number of uses for electricity on the farm increased from about 35 in 1925 to more than 250 at present. The number of domestic uses are greatest at the present time, but near that number are the uses in crop, animal, and poultry production. It appears that electric power on the farm will help to make crop-drying practical, and that in turn may result in important changes in some grain and hay harvesting and storage practices.

The heat pump provides one of the most challenging and interesting applications of rural electric power yet developed. The heat pump, as the name implies, can be used to transfer heat into or out of a given space. In the farm home or other buildings it would provide heat during the cold season and remove excess heat during the warm season. However, before the cost of this equipment and its operation can be reduced to the economical range for general use, several technical mechanical and electrical problems must be solved. Johnson (1951) discusses such problems and, in addition, proper heat source, house design, reliability, and serviceability. It is quite possible that widespread use of the heat pump may develop during the next decade.

c. The Airplane. As a source of power for executing agricultural operations, the airplane will undoubtedly come into much greater prominence during the next decade. More economical and effective dispersing of dusts, fertilizers, seeds, and sprays by aircraft is indicated in research results being obtained by the Texas Engineering Experiment Station (1952). The first phase of the research culminated in the design and construction of an experimental airplane (Fig. 2) that is designed to meet the requirements specified by agricultural pilots.

Lehmann (1952) assembled information on the agricultural use of airplanes. His report indicates that about 5,000,000 acres of farm land were treated in California by aircraft in 1951. The area treated was almost double that treated the previous year. The Kansas reports showed an increase from 419,500 acres in 1948 to an estimated 1,000,000 acres in 1950. There have been similar increases in other areas.

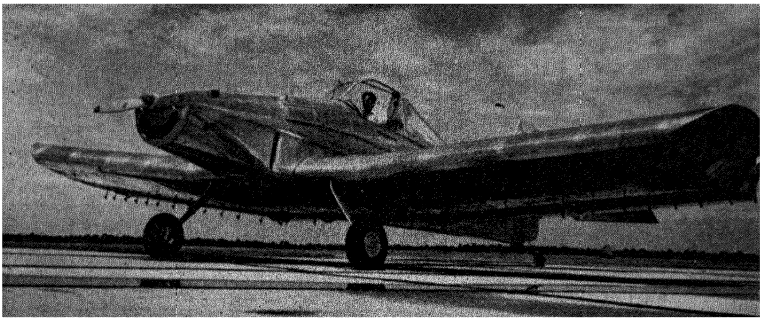

FIG. 2. An experimental airplane designed to meet the requirements specified by agricultural pilots. Provision is made for a quick change of equipment in preparation for either dusting or spraying. (Courtesy of Texas Agricultural Experiment Station.)

2. Soil and Water Management

It is a well-recognized fact that variations in weather have a great influence on the yield of crops. Thus far enough has been learned about this problem to indicate ways in which the farmer may, in a measure at least, reduce the damaging effects of weather irregularities. Such measures include drainage, irrigation, improved infiltration and water-holding capacity of soils, and advanced practices for conserving the top soil.

a. Surface-Mulch Farming. The ways in which crop residues on the surface of the soil aid in maintaining a high water-infiltration rate, the conditions under which they reduce evaporation, the extent to which they prevent soil loss, and the extent to which they influence crop yields as compared to other methods of soil management, are subjects that have been discussed by Duley and Russel (1939, 1942a, 1947, 1948), Carter and McDole (1942), and Larsen and Joy (1943). Mulch farming and related machinery problems have been discussed by Duley and Russel (1942b) and Hurlbut (1950).

In the surface-mulch farming system, one can quickly recognize all of the perpetual machinery problems involved in providing time-tested practices of good crop husbandry plus the problem of working through, and under, a cover of crop residue. In general, this practice appears best adapted to relatively dry or warmer areas, where a small delay in planting time is less serious than in areas with a shorter growing season.

There are at least two basic problems involved in utilizing crop residues for mulches, and, as one might expect, both of them have agronomic and engineering implications. They are: first, to provide as good a seedbed at seeding time as can be had with timely plowing and the usual

secondary tillage operations; second, to keep the crop residue on or near the surface of the soil during the sequence of tillage and seeding operations.

The widespread interest of farmers and the active research in mulch-farming indicate substantial adoption of this practice in the future. One prominent manufacturer is marketing a new stubble-mulch tiller for the first time in 1953. Poynor (1950) reported the development of this new tiller (Fig. 3), a multiple-purpose machine designed for use in row

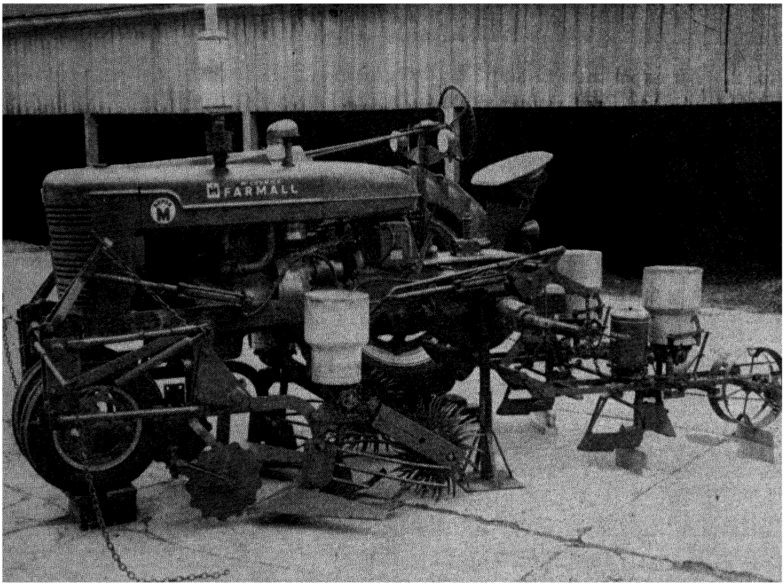

FIG. 3. An experimental machine designed for tilling, fertilizing, and seeding in one operation. The front tillage units are designed to loosen soil beneath a crop-residue cover and deposit chemical fertilizer in bands. The rear unit consists of equipments for seeding and depositing starter-fertilizer near the seed. (Courtesy of International Harvester Company.)

crops. It is designed to perform basic tillage, planting, cultivating, and fertilizing operations. This development also indicates that a serious effort is being made on the part of industry to simplify the machinery requirements for producing row crops.

b. Runoff–Water-Control Systems. Advanced engineering techniques for design of runoff–water-control systems are being studied. New techniques give some promise of reducing the cost of terrace systems and indicate that such systems can be made more compatible with mechanized farming operations. Farm water-control systems are of the perma-

nent type and have a considerable influence on farming efficiency. They deserve the attention of a competent designer.

Wittmuss (1950) studied the design of terrace systems on five farms and found that by relocating terraces, using variable slope in terrace channels, and relocating waterways, he could accomplish a 28 per cent (average) reduction in irregular areas; a reduction of 6.6–15.4 per cent in terrace length required per acre in four out of five fields studied; and a 28 per cent reduction in length of waterways required per acre. These data indicate that water-control systems for land areas being operated under close economic limits should be planned in accordance with good engineering practices. This means that carefully prepared plans and design details should be completed prior to the time construction is started.

c. Irrigation. The real meaning of the term "irrigation farming" is becoming clearer each year as the results of irrigation research are compiled and analyzed. It means something more than merely supplementing rainfall. Land and water are two costly resources in irrigated areas, and the development of both of them requires special planning in order that optimum returns may be obtained. The basic decision a farmer considering irrigation must make rests on whether or not he wants to become an irrigation farmer. The decision *does not* rest on whether or not to build a system that will supply additional water for his crops. There is a big difference between these two considerations.

Basically the principles of irrigation farming in subhumid areas are the same as those developed for arid areas, even though somewhat different problems are encountered. The basic requirements from the standpoint of resources are to maintain an optimum level of fertility, to maintain good soil tilth so that the soil will respond favorably to water, and to apply the optimum amount of irrigation water on a timely basis.

There is some evidence in recent irrigation research at the Nebraska Agricultural Experiment Station that timeliness in irrigation may be a factor of considerable importance. This is based on the observation that the efficiency of irrigation in Nebraska is now about 25 per cent and on the reasoning that if irrigation efficiency could be increased to 50 per cent, it would be possible to double the present usefulness of water resources. Increased knowledge of the timeliness factor may be an important step toward this goal. Studies of the timeliness factor are now under way at several experiment stations.

Some basic research is being devoted to methods of water application, considering not only the mechanics of water distribution but also the problem of soil conservation as it is related to methods of irrigation.

Erosion on irrigated lands is a factor that has not yet received the attention it deserves.

All evidence available indicates a large expansion in irrigated acreages during the next decade. Good irrigation farming is scientific farming of the highest order.

3. Harvesting and Storing Grain

Maximum harvests rather than maximum yields are what the growers want. Tremendous harvesting and storage losses are reported each year because of deficiencies in harvesting practices and storage practices. This area offers the agricultural engineer one of his greatest opportunities to increase efficiency in agricultural production. Agronomic research has been very successful in increasing crop yields and has advanced much farther than has the agricultural engineers' knowledge of harvesting and storage requirements.

a. Some Harvesting and Storage Losses. Fenton and Swanson (1932) report that replies received from 297 farmers indicated that 60 per cent of them had suffered damage to wheat in farm storage. The average amount damaged per farm was estimated at 1000 bushels. If we consider the four-year period 1927–1930, the amount of wheat unfit for milling arriving from Kansas at terminal markets varied from 1 bushel in 8 in the years with favorable harvesting weather to 1 bushel in 4 in the unfavorable years. Although this grain is not a complete loss, it is subject to a substantial discount.

Lemley (1951) verbally reported that of 10,037 bins of farm-stored wheat sampled in 1950 in Nebraska, 1190 were declared ineligible for loans at the outset because of excess moisture, sprouts, or "sick wheat." During a reinspection in November and December, 334 loans on wheat which contained about 13.5 per cent moisture were called up for payment because the grain was deteriorating rapidly. These data indicate that about 15 per cent of the wheat was stored at a moisture level too high for safe storage. It is not uncommon for farmers to store only the driest wheat harvested.

Quisenberry (1949) indicates that annual grain losses in the United States have been estimated at 10–15 per cent of the crop, although no exact figures are available. He refers to estimates of the Food and Agriculture Organization which indicate that the present world losses of grain in storage amount to about 26 million metric tons, roughly equivalent to 950 million bushels of wheat per year, or about 6.6 per cent of the total cereal production of its forty-eight member countries.

The losses of corn occurring in the field and in storage are of considerable economic importance. When ear corn reaches the level of

moisture safe for cribbing, the "normal" (expected minimum) field losses, consisting of shelled corn and ears dropped, increase at a rate of about 3 per cent per week for a period of about four weeks, with the loss thereafter increasing at a rate of about 1 per cent per week. The normal loss at the earliest safe cribbing time seems to be near 4 per cent. The expected grain losses, under favorable harvesting conditions, are shown in relation to kernel and cob moisture content of ear corn. Table I is based on data reported by Shedd (1933), Smith *et al.* (1949), and Kiesselbach (1950), and on unpublished data recorded by Arms and Hurlbut of the University of Nebraska.

TABLE I

Expected Total Field Loss (Per Cent) of Corn Harvested under Favorable Conditions in Relation to Moisture Content of the Kernels and Cobs

Crop characteristics	Mature	10	20	27	34	41	49
			Days after maturity				
Kernel moisture, %	34	26	20*	17.5	16	15	15
Cob moisture, %	54	46	30	24	21	19	17
Expected field loss	1	2	4	7	10	13	15

* Normal harvest starts at a kernel moisture of 20 per cent.

The amount of damage that occurs to ear corn in storage is not easily determined because of the large variation in results obtained in different years. Shedd (1946) studied the effect of moisture content on grades of corn in crib storage during the period 1937–1946. He found that the percentage of cribs containing corn with 20.1 per cent moisture or less varied from year to year as follows: 1937–38, 90 per cent; 1938, 100 per cent; 1940–41, 89 per cent; 1941–42, 85 per cent; 1944–45, 35 per cent; and 1945–46, 19 per cent. He observed that it is under favorable conditions only that a moisture level of 20 per cent will assure the production of grade No. 1 or No. 2 by the customary methods of crib storage. The corn stored at 20 per cent moisture or less, in the 360 cribs observed, graded as follows (on a damage basis only) : No. 1, 36 per cent; No. 2, 26 per cent; No. 3, 14 per cent; No. 4, 12 per cent; No. 5, 6 per cent; and sample grade, 6 per cent. Loss of some of the original good quality of ear corn subsequent to harvest results from a lack of ventilation. Poor ventilation may be caused by imperfect machine husking as well as by imperfect storage structures.

Field and storage losses in the production of grasses and legumes are generally recognized as being rather high. The importance of these field losses is indicated by Grandfield (1951), who collected data from widely

scattered fields of alfalfa in Kansas. He found that with the present farm methods of harvesting the seed loss ranged from 17 to 46 per cent. On the other hand, Hanson and Harrison (1950) report that with present harvesting methods farmers save only about 40 per cent of the alfalfa seed actually produced.

There is evidence to indicate that grain producers have always been reluctant to let grain crops stand in the field until they have dried naturally to a moisture content safe for storage. They have made use of the header, the binder, the swather, and the corn crib as intermediate steps in their efforts to reap crops at the earliest possible time. These intermediate harvesting measures and the lack of a continuous and easily controlled source of power on the farmstead apparently have not been conducive to the development of equipment and structures suitable for curing the crops after they have been placed in bulk storage. However, these measures do indicate that the grower considers an early harvest of considerable economic importance.

Briefly, an important limiting factor in modern grain production is the inadequacy of 19th-century storage structures used in combination with 20th-century harvesting machines. At the present time, it appears that forced-air drying will be at least a partial answer to this problem.

The problem of harvesting and drying grain containing more moisture than is permissible for safe, long-time storage is bounded by agronomic factors governing the time of harvest and by pathologic factors governing the environment in storage. Basic factors to be considered in addition to maturity of the grain and character of the air available are moisture and temperature of the grain, soundness of the kernels, foreign material present, and the period of time suitable for drying.

b. Moisture Limits for Some Harvesting Machines. Field tests conducted at the Nebraska Agricultural Experiment Station during the period 1948–1951 have demonstrated that the present-day combines and corn shellers will do a reasonably good job of harvesting oats, wheat, brome grass, legumes, and corn containing 25 per cent moisture. Wheat has been combined at 28 per cent moisture; oats, brome grass, and sweet clover at 32 per cent moisture, and corn containing up to 30 per cent moisture has been picked and shelled with an improvised trailer-mounted sheller.

Harold Hummel, a farmer near Fairbury, Nebraska, combined a 3-acre field of brome grass mixed with alfalfa which yielded seed containing about 51 per cent moisture. The seed from another 5-acre field was harvested with 46 per cent moisture. About 200 bushels of this seed was dried with unheated air to 12.2 per cent moisture in 84 hours of fan operation spread over a period of ten days. The seed was dried in

a specially adapted trailerbed (Fig. 4) connected to a fan which supplied forced unheated air. Later the same month, Mr. Hummel combined 15 acres of sweet clover seed which yielded a total of 90 bushels of clean, dried seed. The depth of dry clover seed in the trailer was measured at 19 inches after it had been reduced from 23.2 to 10.8 per cent moisture in 109 hours of fan operation. The dry brome grass and clover seed possessed 88 and 97 per cent germination, respectively, on standard test.

Theodore Wirth, a large-scale farmer near Nebraska City, has shelled

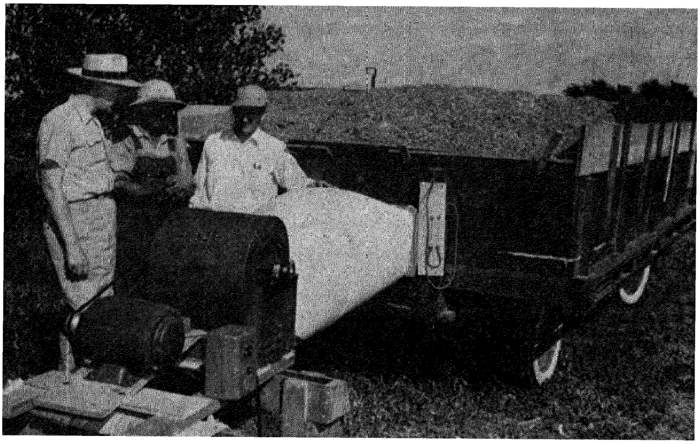

FIG. 4. A trailer equipped with an air distribution system adequate for drying grass and legume seed with unheated forced air on a Nebraska farm. An electric motor is used to drive the centrifugal fan which supplies the air. (Courtesy of Nebraska Agricultural Extension Service.)

corn at 35 per cent moisture in a commercial-type sheller. He depends upon heated air for drying the grain in a batch-type drier (Fig. 5).

Experiences and observations in Nebraska confirm brief but early reports made by Duffee (1927), Miller (1927), Aspenwall (1929), McGregor (1925), and Logan (1931), indicating that existing harvester-threshers and corn shellers could harvest grains and soybeans the moisture content of which was well above the limits for safe storage. These reports also serve to emphasize the difficulty involved in determining the proper time to commence the harvest when the crop has to be stored in existing structures.

The fluctuation of moisture in small grains during the harvest season is a factor of considerable importance. It may be quite large and sometimes changes rapidly. Goss (1929) reported that the moisture content

of oats, after a heavy dew, dropped from 20.4 per cent at 9:00 A.M. to 11.4 per cent at 11:00 A.M. Cromer *et al.* (1929) reported on wheat with variations in moisture content ranging from 3 to 8.3 per cent in one day. Fenton and Swanson (1932) reported a case where a field of wheat at Manhattan, Kansas, lost 26.1 per cent moisture (35.5–9.4 per cent) in five days.

c. Conditioning Wheat and Shelled Corn for Storage. Moisture and heat set the stage for damage to grain in storage. They govern insect damage, molding, heat damage, sprouting, and rotting. When starchy

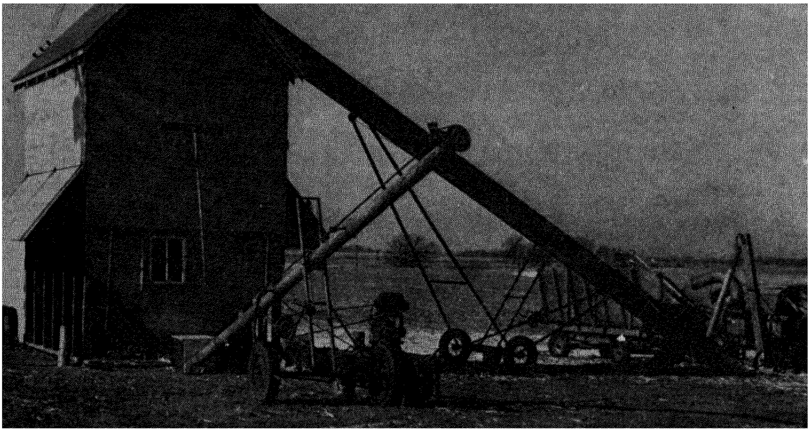

FIG. 5*A*. A batch-type column drier using heated forced air as the drying medium. The grain is first elevated into an overhead hopper. Then it is fed through control gates into the drying columns. After the grain has dried sufficiently, it is fed through control gates into the cooling columns. (Courtesy of United States Department of Agriculture Division of Agricultural Engineering.)

grain is kept at 12 per cent moisture or less, it resists nearly all kinds of damage that occur in storage. But even when grain is put into storage at 12 per cent moisture or less, there is no guarantee that it will remain at that moisture level. During the winter, warm moist air moves upward from the center of the bin to the cooler portion at the top where it loses some of its moisture, with the result that the moisture content of the grain in that zone increases. Fortunately, these temperature and moisture changes can be controlled with forced air ventilation.

The theoretically ideal harvest time for starchy grain is probably near the time of maximum growth, when the moisture content is about 34 per cent. This leaves 22 per cent moisture that must be removed. With the use of heated forced air and a batch drier, this amount of mois-

ture could be extracted from grain and the early harvested crop could then be stored safely if it is ventilated seasonally to equalize temperatures.

(1) Insects and mold cause damage. Most damage in stored grain is caused by insects and fungi. The number of insects in a bin of any

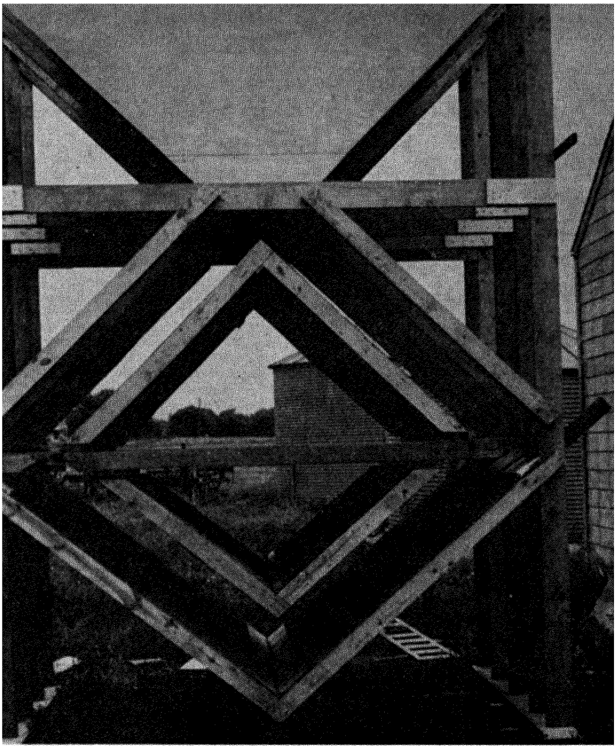

FIG. 5*B*. This is an exposed view of the columns which serve for drying and cooling grain in the batch-type drier. The columns are divided by control gates so that air is drawn inward through the cooling section or lower half of the columns. The air then passes through a heater before it is forced outward through the upper half of the column where most of the drying is done. (Courtesy of United States Department of Agriculture, Division of Agricultural Engineering.)

kind of grain varies directly with the amount of heat and moisture present. Insects damage the grain in two ways: first, by eating part of the kernels; and second, by producing more heat and moisture by their metabolic activity and rapid reproduction. In the case of some insects, several generations are produced in a year. Grain that is kept cool and dry provides an unfavorable environment for insects.

According to Christensen (1951), fungi, like insects, thrive in grain that is damp and warm. Fungi grow more rapidly in wheat and oats than they do in corn, except when the kernels of the corn have been damaged. Mold is the visible proof of the destructive activity of fungi. The growth of mold is influenced by temperature but not as much as by moisture. Scientists agree that molds are the primary source of heating. The apparent effects of mold are reduced viability of seed and off-odors and off-flavors in the products made from the grain.

Temperatures near freezing may slow the growth of mold, but some mold growth may continue at temperatures ranging from 20° to 120° F. Mold spores are ubiquitous airborne organisms. It is practically impossible to eliminate them by purifying the grain or the air. The best safeguard is to keep the grain dry and cool.

(2) Blower is important. Present farm drying methods depend on the use of forced air, either unheated or heated. The "air" factors that can be controlled most easily are the amount of air circulated per bushel of grain and the temperature of the air. Since the circulation of air is involved in all present methods of drying, the air blower probably should be considered first if one is planning to install a drying system.

The air blower will "pump" the most air per horsepower input when the resistance in the air passages is lowest. As the resistance to air flow increases, the power required to produce the flow of a given quantity of air per unit of time also increases. Therefore, it is extremely important to choose fans carefully with due consideration of the job to be done. If the characteristics of the job are known, the fan can be correctly selected from data supplied by reliable manufacturers. The manufacturer's fan data will express resistance to air flow in terms of "inches of water column."

Fans designed for "space" ventilation generally are not suitable for use in drying grain under farm conditions. In general, a fan for drying grain in bulk storage should be a nonoverloading type. It should deliver at least 3 cubic feet of air per minute for each bushel of wheat or corn and do this against a resistance pressure of about 2½ inches of water column.

(3) Depth of grain a factor. Tests show that the power required to force a given amount of air through grain increases rapidly as the thickness of the grain layer is increased. With the air flow per bushel constant, doubling the depth of the grain in the bin will increase the power requirement about eight times. Tests indicate that where grain is dried in bulk-storage bins, as in Fig. 6, a reasonable power-depth relationship occurs when air is forced through about a 6-foot layer. Greater depths of grain can be dried economically when it is necessary to remove

only 3 or 4 per cent moisture. In this case, lower rates of air flow per bushel may be used effectively.

(4) Heated or unheated air? Heated air has a higher moisture-vapor carrying capacity than unheated air. For this reason, heated air has the ability to dry grain faster and to a lower moisture level. But air that is warm and also moist favors mold growth. When hot air is used for drying, it becomes moist before it leaves the bin. Therefore, the job must be done in a relatively short period of time, and the grain should be cooled with unheated air before the fan is stopped.

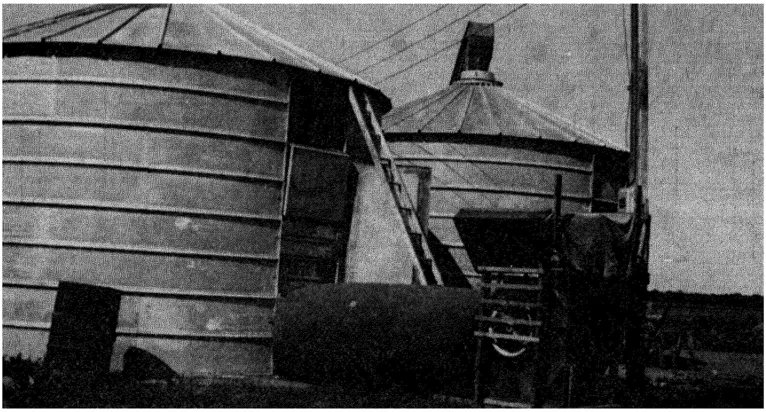

FIG. 6. A centrifugal-type of fan connected to a circular steel bin by a canvas duct. High moisture grain can be dried successfully in bulk storage in Nebraska and neighboring states with the use of unheated forced air. (Courtesy of Nebraska Agricultural Experiment Station.)

As a rule of thumb, with each increase of 17°–20° F. in temperature of air of given humidity, the moisture-vapor carrying capacity of the air is about doubled. When the temperature is raised the relative humidity is lowered. Air of low relative humidity can dry grain to a low moisture content.

Table II taken from Engineering Data on Grain Drying (1948), published by American Society of Agricultural Engineers, shows the mini-

TABLE II

Adsorbed Moisture in Shelled Corn in Equilibrium with Air of Various Humidities at Room Temperature (approx. 77° F.)

Relative humidity of air, %	30	45	60	75	90	100
Moisture content, % (wet basis)	8.4	10.4	12.9	14.7	19.0	24.0

mum moisture content of corn that can exist at different relative humidities. For example, a minimum relative humidity of 60 per cent will dry corn near to 12.9 per cent moisture when the corresponding temperature is 77° F.

If air of low relative humidity is applied to grain in bulk storage, it may "overdry" the grain. This predominant characteristic of heated air is the reason why fan-and-heater combinations are used most effec-

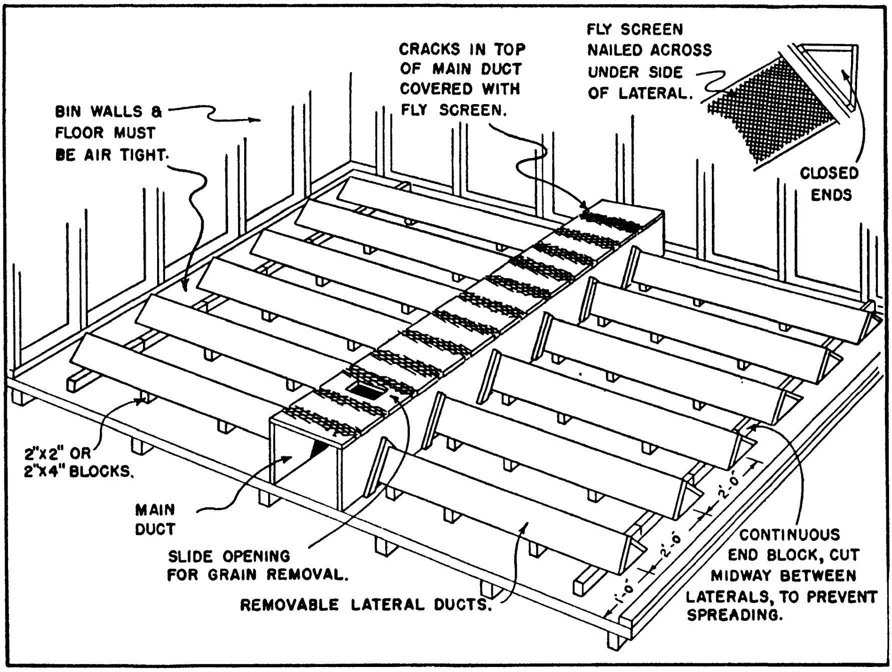

FIG. 7. A plan for adapting a grain bin for forced-air drying. The fan is attached to the main duct, which rests on the floor.

tively in conjunction with batch driers. When heated air and a batch drier are used together, the grain is dried rapidly in relatively thin layers, and there is careful control of the length of the drying period. When heated air and a batch drier are used, grain must be dried and then cooled before it is put into storage. A batch-type column drier is described in the United States Department of Agriculture Leaflet No. 134. (1951).

(5) The air distribution system. A diagram containing recommendations for adapting the floor and walls of a bin in Nebraska for drying

with unheated air is shown in Fig. 7. The following is a summary of present recommendations.

(6) The bin. The bin walls and floor should be airtight. (A paper lining is sometimes necessary). The depth of high moisture (25 per cent) oats, corn, and wheat should be limited to 6 feet measured above the lower edge of the lateral ducts. An outlet should be provided for the exhaust air approximately two times the size of the main duct cross section and located so as to prevent recirculation of the moist air.

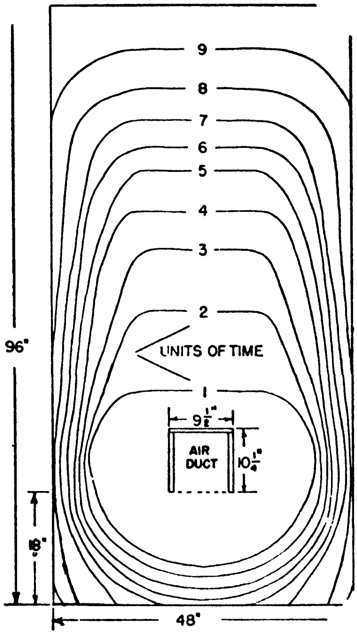

FIG. 8. A schematic diagram showing progressive drying in a 100-bushel experimental bin. Drying medium was unheated forced air.

(7) The blower. The blower should be capable of producing a flow of air in cubic feet per minute equal to three times the bushels of grain stored, against a static pressure of 2.5 inches of water. The backward-curved centrifugal blower, as well as some of the newer propeller types, serve very well for farm use. Fans should be selected only on the basis of data published by the manufacturers. The ASAE Engineering Data on Grain Storage (1948) show the pressures that are required to force air through different kinds of grain and through different depths of grain.

(8) Main duct. A minimum cross-sectional area of 1 square foot for

each 1000 cfm. of air flow is recommended. It is sometimes desirable to build the main duct in sections for easy removal when the bin is being cleaned. The duct can be located in the center of the bin or along one side of it.

(9) Lateral ducts. These are spaced 2 feet apart near the floor. The laterals may be slipped under cleats placed around screened openings in the main duct. It is advisable to place screen on the open side of the lateral. Successful experiments have been conducted with ducts raised 18 inches above the bin floor and spaced 4 feet on centers. The grain dries in progressive layers or zones, as shown in Fig. 8.

Evidence available points to developments in harvesting and storage practice which will shorten the period between the time a crop is mature and the time it is harvested. This appears to be a basic objective with all crops and will require the use of crop conditioning equipment. A move in this direction will also reduce harvest delays caused by wet grain.

Greater precision in executing planting and harvesting schedules may make it possible to keep the land in crops more continuously where moisture is not the limiting factor. For example, crops of corn, wheat, and clover may all be grown within a period of two years. It will also make it possible to get greater use from harvesting machines.

There probably will be a considerable increase in the amount of corn harvested with picker-shellers. This will undoubtedly revive efforts directed toward adapting a combine for harvesting corn. The two basic problems involved in adapting a small-grain combine for harvesting corn are: first, getting the ear off the stalk; and, second, discarding the stalk without having to process it. These two problems are not without a practical solution.

4. *Harvesting and Storing Hay and Forage*

a. Main Sources of Loss. Aside from purity and texture, the important quality factors in good hay are associated with, and greatly affected by, the time of cutting and the curing practices. But even with the best known farm practices, haymaking in humid and subhumid areas is a gamble with the weather. Much hay must remain in the field one or two nights even in fairly good weather and so is wet by dews. Large quantities may be rained on and require extra handling. The result is a major loss of nutrients and hay highly variable in quality. There are two main sources of loss in sun-cured hay: first, shedding of leaves and, second, losses due to dews and rains followed by a period of exposure to hot sunshine. Bechdel *et al.* (1940) say that proteins may be reduced under poor curing conditions as much as 30–50 per cent, carbohydrates

as much as 30–40 per cent, fats by 30 per cent, and minerals by 20–25 per cent.

b. Sun-Cured vs. Dehydrated Hay. Bechdel *et al.* (1940) report the results of five hay feeding tests, and in every test there was evidence of the superior feeding value of the dehydrated hay as compared to that of sun-cured hay from the same field. High-grade sun-cured hay, not exposed to rain, was used in the tests.

Hauge and Aitkenhead (1931) report that certain enzymes are responsible for the destruction of vitamin A in field-cured hay. Mitchell and Hauge (1946) report that the enzymic destruction of carotene in alfalfa under good curing conditions may amount to 45–80 per cent of the carotene originally present. This view is based chiefly on the observation that autoclaving or blanching of alfalfa prevents destruction. The inactivation of the enzyme by heat was found to be a function of both temperature and time.

The possibility of a higher amount of ''grass-juice factor'' in dehydrated forages is reported by Hart (1940). This factor appears to be preserved by quick drying.

c. Silage vs. Dehydrated Green Corn. Tests of silage versus dehydrated green corn were also conducted by Bechdel *et al.* (1940) over a period of two years at the Pennsylvania Agricultural Experiment Station. Dairy heifers were fed silage and dehydrated corn in equal amounts of dry matter. Both feeds were considered quite palatable. Heifers fed the dehydrated product displayed a thriftier appearance and showed appreciably higher gains.

d. Need to Define Quality. The physical and chemical properties of hay or other animal feeds are the intermediate quantitative data that constitute the link between animal nutrition, crop improvement, and engineering improvement of methods and equipment for harvesting, handling, and storing animal feeds. From the engineering standpoint, there is need for a more precise definition of hay quality. Improvements in production, harvesting, storage, and handling methods and equipment can be evaluated only in terms of tangible, measurable, specific properties influencing the quality of hay. The investment a farmer has in hay and forage crops up to the time of harvest seems to justify a reasonable increase in the cost of harvesting if that will insure a better-quality product.

e. New Developments. Dudley and Jones (1948) report on experiments to determine the benefits from crushing hay. Special attention is being given to design changes which will help to reduce the leaf loss now experienced in raking operations. Elliot (1950), Bainer (1951), and

Giles and Routh (1951) report new data applicable to the design of hay rakes.

The use of forced air drying of hay containing 40 per cent moisture or less is being tried over a wide area to reduce the time hay is exposed

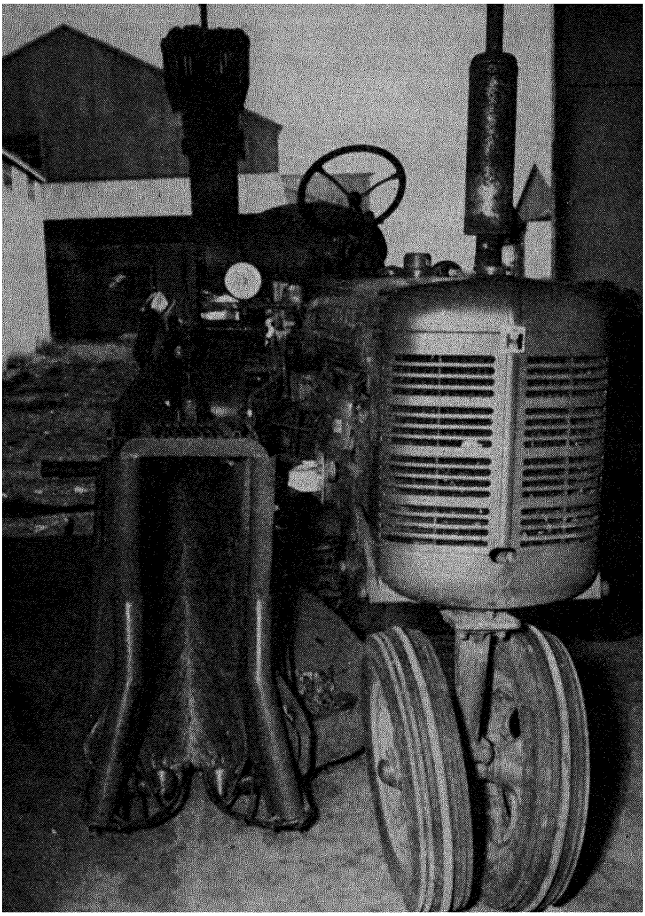

FIG. 9. Front view of an experimental brush-type cotton stripper used during the 1949 season in Oklahoma. (Courtesy of Oklahoma Agricultural Experiment Station.)

to weather elements. In some areas farmers have the choice of using either heated or unheated air.

Commercial dehydrating plants are being used widely throughout the United States. Freshly harvested (chopped) hay is delivered directly

to the dehydrator, where it is dried quickly, ground, and then sacked. Most of the dehydrated hay is used in commercial feeds.

4. *Cotton Production*

a. Weed Control and Defoliation. Although many developments have occurred recently in cotton production in the United States, many more developments and improvements are necessary before complete mechanization is reached. Two of the biggest barriers to complete mechaniza-

FIG. 10. An experimental cotton stripper developed in Texas. The problem of developing a low-cost harvester is difficult to solve satisfactorily. (Courtesy of Texas Agricultural Experiment Station.)

tion of cotton production are imperfections of the practices of defoliation and weed control. Advances in weed control will require improved planting equipment and better cultural practices. New planting equipment and practices are influenced by soil type, seedbed preparation, and seed conditioning. Problems in cotton production remaining to be solved are interrelated and very complicated. Practical solutions for these problems will require the best efforts of many specialists.

It appears that the present research work in cotton production may yield important dividends during the next decade. The importance of mechanical harvesting alone is well expressed in the estimate that 5000 mechanical cotton harvesters will replace 100,000 hand pickers.

b. New Harvester Developments. The recent development of a brush-

type cotton stripper (Fig. 9) at the Oklahoma Agricultural Experiment Station is reported by Oates (1952). This harvester uses pliant stripper brushes which remove the cotton from partially dead plants. Figure 10 shows another low-cost experimental cotton harvester being studied by the Texas Agricultural Experiment Station. These relatively low-cost machines may provide the answer to a completely mechanized cotton harvest in the Southwest.

c. *New Ginning Developments.* New and improved varieties of cotton have better spinning properties, longer fibers, and other desirable characteristics. However, subsequent to harvest a large part of the value of the improved crop can be nullified by poor ginning procedures and equipment. A United States Department of Agriculture release (1950) contains an estimate that losses resulting from poor ginning of cotton total about $15,000,000 per year in the United States.

New gin saw speeds and loose seed rolls will increase gin capacity about 20 per cent. Better power usage can be obtained with improved piping, improved fans, and better methods of operation. New recommendations for design and maintenance of gin saws have been formulated. Handling equipment that prevents mixing a pure seed during the ginning process has also been developed.

6. *Equipment for Applying Fertilizers*

With some 4000 patents to cover the numerous types of fertilizer-dispensing mechanisms, according to Cummings *et al.* (1950), and a listing of 131 manufacturers by Cummings (1950), it would seem that no fertilizer equipment problems could possibly exist. In addition, a directory of machines, for use in experimental application of fertilizer, is offered by French (1950). The directory lists 48 different experimental machines.

Hyland (1950) says that since the introduction of commercial fertilizers, designers have been trying to build a machine that will apply a wide variety of fertilizers satisfactorily. This has been a constant struggle because of the rapid changes in the fertilizer industry and the wide variations in fertilizing practices recommended in different areas.

Reduction of corrosion, standardization of fertilizer characteristics, and more concentrated fertilizer will probably be the trends in the near future. Guelle (1950) states that it is doubtful if any great headway can be made toward providing proper equipment until the fertilizer manufacturers get together with the equipment manufacturers and develop some basic standards for fertilizers and associated equipment.

Lockwood (1950) says that fertilizers of the future will contain more plant food and less moisture and that more granular fertilizer will be

made and used. These trends are already under way and may develop even more rapidly than they have in the past decade.

Gull (1950) discusses the use of liquid and gaseous fertilizers. He says that they are less versatile than solid fertilizers from the standpoint of being adapted to all soils. Soils of poor physical condition which become cloddy do not absorb the gas fast enough. Price differentials will probably influence the choice between liquid and solid sources of nitrogen. However, anhydrous ammonia supplies only nitrogen and, therefore, may be at some disadvantage in areas where two or more of the major plant foods are required.

Scarseth (1950) describes an agronomists "dream machine" having three hoppers with feeds under lever control from the operator. In variable fields the operator could apply extra fertilizer in the less fertile spots. Although this idea seems highly theoretical at first thought, observations on variation in the production level of field areas emphasizes its importance.

Cummings (1950) observes that many opportunities exist for future developments. This includes not only dispensers for solid fertilizers over a wide range of conditions but also includes the application of liquid fertilizers either to the soil or directly on the plant, the development of equipment for airborne use, bulk-handling equipment, gas and liquid injectors, and devices for applying fertilizer in irrigation systems. The trend in the future will be to continue improving both fertilizers and fertilizing distributing equipment on an undiminished scale.

7. *Mechanization of Special Crops*

Butt and Kummer (1951) report that the advent of mechanized methods for harvesting peanuts has resulted in a demand for information on artificial curing of this crop. Experimental peanut pickers and combines have harvested peanuts successfully at all stages of curing from freshly dug peanuts (35–60 per cent moisture) to field-dried peanuts (6–8 per cent moisture). They predict that mobile peanut harvesters will come into general use. A peanut harvester is described by Stokes and Reed (1950).

Kramer (1951) reports on engineering aspects of rice production. Maximum quality in rice was obtained when it was harvested at 20–26 per cent moisture (wet basis). This poses a drying problem which is being studied in an orderly manner.

Martin and Humphrey (1951) in a report on potato harvesters say that the development of adequate mechanical harvesting equipment has generally been left to the individual farmer. Practically all of the potato combines now in use have been built in local or farm shops. They

describe both single-row and two-row sacking machines and single-row and two-row bulk-handling machines.

Jones *et al.* (1951) report the development of a multiple-use drill. This machine performs tillage operations, sows the seed, and applies the fertilizer in a single operation. Consideration is being given to the development of multiple-use machines at several different experiment stations.

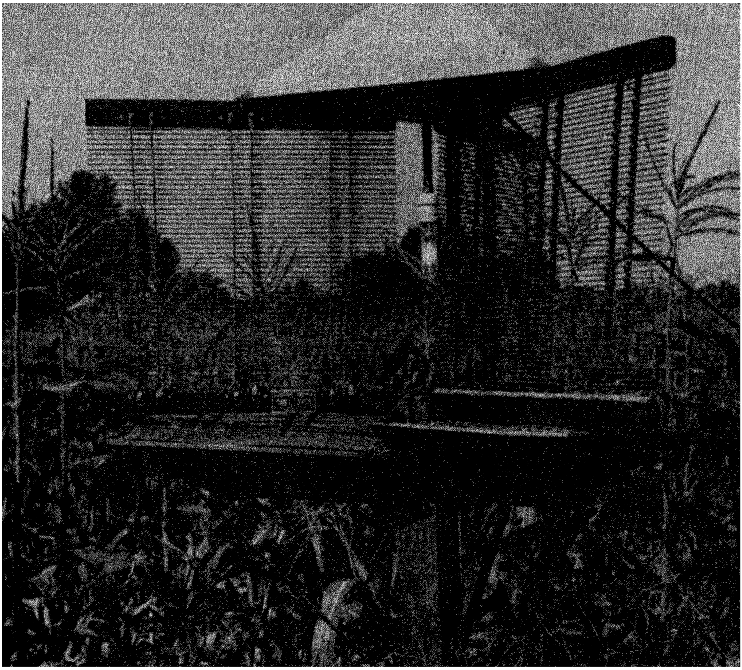

FIG. 11. An experimental electric trap developed to destroy insects at night. Different arrangements of the grid-panels are being tried along with different kinds of lamps. This trap has an electric lamp in a Y-array of panels. (Courtesy of United States Department of Agriculture Division of Rural Electrification.)

Studies on the threshability of Ladino clover are reported by Long (1951), and a vacuum unloader for handling forage is discussed by Terry (1949).

Problems in the design of chemical weed-control equipment for row crops are discussed by Barger *et al.* (1948). They conclude that although some of the equipment design problems have been fairly well solved, there are many yet remaining.

Barmington (1948) and McBirney (1948) discuss experimental work with beet planters. Thinning the stand and weed control are two basic problems which remain to be solved satisfactorily in the production of

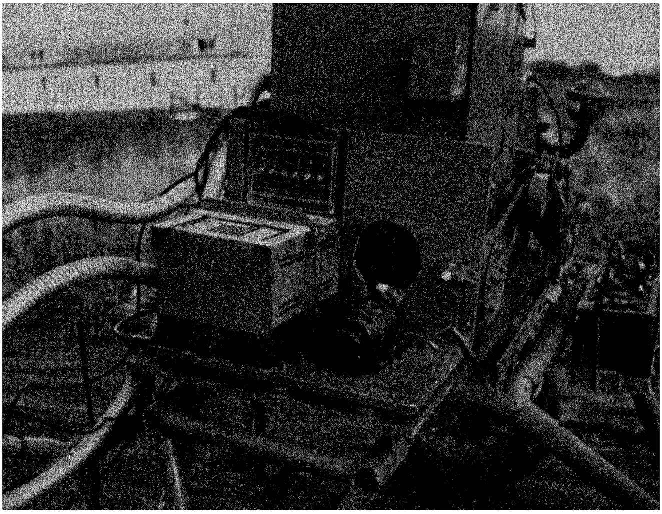

FIG. 12A. The storage battery and auxiliary electrical equipment used on an electrostatic dusting machine developed in Michigan. This development shows some promise of reducing the amount of dust required and better distribution of dust on the plant surfaces. (Courtesy of Michigan Agricultural Experiment Station.)

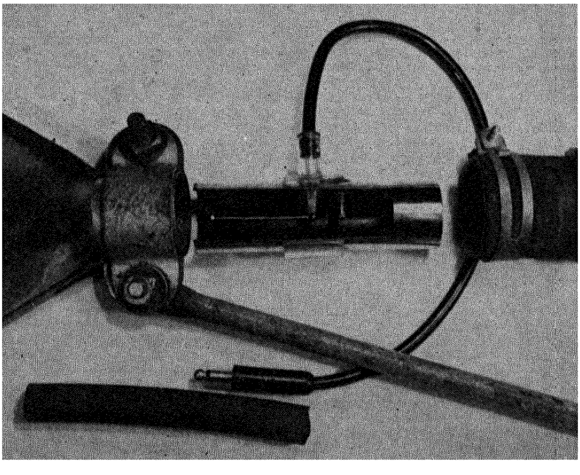

FIG. 12B. A cutaway view of a nozzle used on the electrostatic dusting machine.

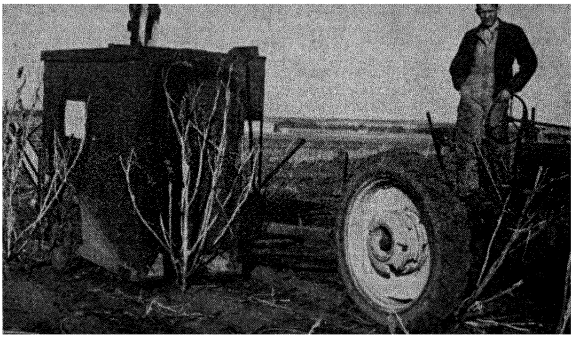

FIG. 13*A*. An experimental harvester for castor beans developed in Nebraska. The large stripping compartment is designed to reduce shattering loss.

sugar beets. The problem of storing sugar beets with minimum sugar loss is discussed by Hansen (1949). He concludes that trash and dirt in the beet pile should be kept at a minimum. Cooling of the sugar beets with forced air is desirable.

A mechanical onion harvester is described by Lorenzen (1950). A sugar cane harvester is described by Duncan (1950).

Longhouse *et al.* (1950) report on a study of the application of fluidization to conveying grain. Preliminary tests indicate that whole wheat

FIG. 13*B*. The rear view of the castor seed harvester shows the unit for separating the castor beans from the leaves and stems. A raddle located above an inclined apron serves for making the separation.

can be transported with ease in a 1-inch pipe 75 feet long, either vertically or horizontally or both.

Taylor and Deay (1950) report developments in the use of electric lamps and traps (see Fig. 11) in corn borer (*Pyrausta nubilalis Hbn.*) control.

Bowen *et al.* (1952) report progress in their attempt to utilize the electrostatic forces of charged dust particles in securing higher retention of fungicidal or insecticidal dusts on plant surfaces. The equipment being used for applying charged dust is shown in Fig. 12.

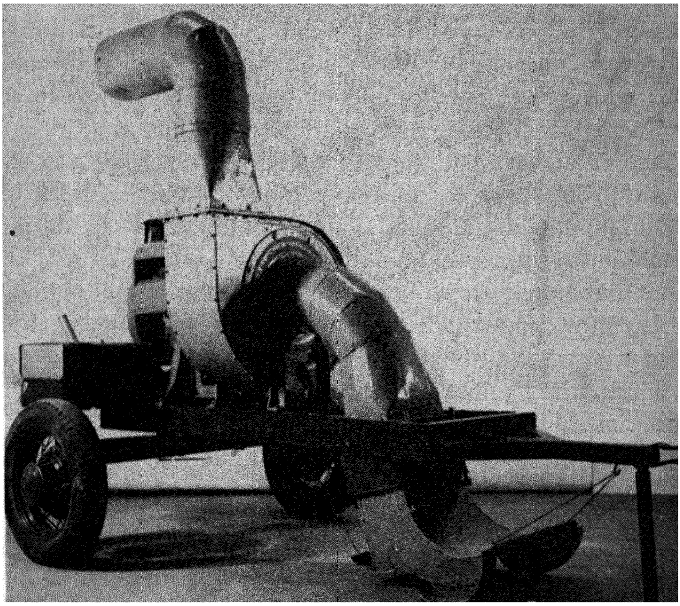

FIG. 14. An experimental vacuum harvester used for small dry windrows of Ladino clover. The fan must move from 2400 to 3000 cubic feet of air per minute for each foot of nozzle width. (Courtesy of Michigan Agricultural Experiment Station.)

An experimental pull-type harvester for castor beans is reported by Arms and Hurlbut (1952), as shown in Fig. 13. A single-row mounted castor bean harvester is described by Baker and Van Horn (1951). A two-row mounted harvester is described by Schroeder and Reed (1952).

Other work under way at different experiment stations includes a vacuum harvester (Fig. 14) for low-growing legume seeds, experimental work on a harvester for pole beans, sweet corn harvesters, raspberry

harvesters, asparagus harvesters, and harvesters for filberts, almonds, and walnuts.

V. Concluding Statements

This report is not intended to give a complete picture of recent developments and future trends in mechanized farming. It should serve to indicate the general character of the efforts of agricultural engineers to improve agricultural production methods.

A critical scrutiny of the work being done indicates that much of the effort now, as in the past, is being devoted to establishing the basic means for mechanizing the present methods used in crop husbandry. The main problems appear to be in the tillage, planting, weed elimination, harvesting, and storage operations. More attention is being devoted to the problem of preserving the original high qualities of crops subsequent to the time of harvest. This is commonly referred to as crop processing.

Thus far, little more has been accomplished than the mechanization of methods of production in existence when man or animals furnished the power. There is much room for improvement in the design of the existing machines. There is also need for development of new machines.

The next important step is to develop carefully engineered systems of production in which machines are designed to work efficiently in series combination and wherein labor can be used more efficiently. There are still almost unlimited opportunities for improving mechanized agricultural production.

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Chemical Weathering of Minerals in Soils

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CONTENTS

I. Introduction

Weathering of minerals in relation to soils has two distinct phases: (a) Past weathering has broken down hard rocks both physically and chemically to form the unconsolidated sands, loams, and clays from which soils may be formed; and (b) present weathering of soil minerals remains the major source of nutrients used by crops, for which the vast chemical fertilizer industry is but a supplement. The first phase concerns the kinds of minerals found in various kinds of soil and soil parent material. The second phase concerns the rate at which ions are released in available form from minerals under specific conditions. As agriculture is intensified in particular areas, the proportion of the nutrients supplied by weathering becomes relatively smaller compared to that added as fertilizers. But even in areas of well-developed agriculture, both in temperate and tropical regions, the weathering release of nutrient elements is of major importance in soil fertility and crop production.

It is the purpose of this paper to examine the processes and products of chemical weathering of minerals in soils from the standpoint of each of these phases.

1. *Definition of Weathering*

The term "weathering of rocks" refers to the changes in degree of consolidation and in composition which take place in the earth's crust within the sphere of influence of atmospheric and hydrospheric agencies. Weathering has two distinct aspects, physical and chemical, each of which can be defined separately. Physical weathering is the change of consolidated rock to the unconsolidated state. Chemical weathering is the change in chemical composition of consolidated or unconsolidated rock. For clarity, the agencies and processes of weathering (the means by which the changes are brought about) will be carefully distinguished from weathering itself (the changes). The term "weathered" means changed physically or chemically, under atmospheric or hydrospheric influences.

Changes in rock composition which are caused by deuteric and hydrothermal agencies are termed "alteration" rather than weathering, although some changes in mineral content of rocks arising through alteration are virtually identical to those arising through weathering. According to Merrill (1906), some scientists have not been precise in making the distinction between weathering and alteration. He defined weathering as the superficial changes in a rock mass brought about by atmospheric agencies and resulting in a more or less complete destruction of

the rock as a geological body. Physical weathering he termed disintegration; chemical weathering he termed decomposition.

a. The Province of Physical Weathering. Although the scope of this paper is limited to the province of chemical weathering, a brief statement is given on the province of physical weathering for purposes of clarification of the interrelationships between the two. Physical weathering is the change from solid massive rock to the unconsolidated or clastic state, under the influence of atmospheric or hydrospheric agencies, as already explained. Polynov (1937) defines weathering as the complex process, cyclic in nature, which causes the breaking down of the monolith of rock or in general, solid body, and produces an increase in surface or interface between it and the surrounding media. It is known that every interface, whether it be the boundary between the solid and liquid or solid and gaseous states, possesses specific physicodynamic properties which become more important quantitatively and qualitatively as the ratio of the interface to the surrounding mass, specific surface, increases. Weathering is thus, according to Polynov (1937), any process which breaks down the large units to smaller "more active" units; and he defines the "crust of weathering" as "that upper part of the lithosphere which consists of the loose products of the disintegration of igneous and metamorphic rocks." Elsewhere he includes disruption of sedimentary rocks and makes clear that he includes processes involving transporation.

Physical weathering or disintegration breaks up the rock into smaller units by mechanical means. The smaller units retain their original identity and composition. A basalt which has been broken down by mechanical means into smaller units can still be recognized as a basalt or, if the particles are sufficiently fine, as its component mineral grains. Physical weathering takes place either through agencies which act on the rock in place or which move the rock about and abrade it. The latter include: (a) glacial ice, (b) moving water, (c) gravity displacement on steep slopes, and (d) wind, for example, sand-blasting. These agencies which move the material about are sometimes excluded as weathering agencies but should surely be included. Physical weathering in place is brought about through five principal processes (Reiche, 1950): (a) unloading, which permits the expansion of rock masses: when confining pressures are lessened by uplift and erosion, cracks and joints form in bedrock; (b) thermal expansion and contraction from insolation, which was once considered a major factor (Polynov, 1937) but has now been shown to be relatively unimportant by Blackwelder (1933) and Griggs (1936); (c) crystal growth, which produces a prying action on rock or mineral—this includes the action of frost and to some extent of crystals formed by chemical weathering, as, for example, the physical weathering of quartz

crystals by iron-oxide films (Humbert and Marshall, 1943) and the crumbling of building stones in Switzerland attributed to the growth of ice crystals and, in the cities, of sulfate crystals in cracks (Quervain, 1945); (d) colloid plucking, the physical rupture caused by shrinkage of colloidal matter with resultant flaking off of the surface of rocks; and (e) pressure and abrasion by plants and animals, for example, disruption of rocks by the enlargement of roots wedged in cracks (Kellogg, 1943, p. 42).

The chief contribution of the physical weathering of rocks to chemical weathering is the increase of specific surface of the material, with attendant increase in reaction rate. Birot (1947) found that rock samples of granite and syenite and large crystals of biotite, muscovite, and orthoclase lost from 1 to 6 per cent of the sample by disintegration into sand particles after being alternately wetted at room temperature and dried at 70° C. Caillere *et al.* (1952) obtained the breakdown of 6 per cent of a slightly weathered gabbro into sand and some montmorin clay by alternate wetting and drying. Simply keeping some material under water can cause subdivision of the particles. Dekeyser *et al.* (1950) boiled mica in water for a long period of time and obtained a clay-size product. Henin and Betremieux (unpublished) obtained this same effect at room temperature. Demolon and Bastisse (1946) found reduction of the particle size of sieved granite after five and fifteen years of weathering in a lysimeter. Wetting and drying can also bring about the formation of new minerals and thus cannot be considered purely a physical weathering factor. For example, Caillere *et al.* (1952) found that when the gabbro suspension was evaporated and then wetted again, the gabbro became coated with a ferruginous crust.

In soils, particles of sand size are almost entirely products of physical weathering (concretions excepted). Practically all particles of silt size are products of physical weathering in cool and temperate climates but are largely products of chemical weathering in tropical climates. Particles of clay size have such high specific surface that every stage of chemical weathering is represented in this fraction, from early stages in glacial rock flour (hornblende, biotite, albite) and intermediate stages (montmorin, kaolin) to highly resistant products and residues (allophane, anatase, ilmenite).

b. The Province of Chemical Weathering. Chemical weathering is the change in chemical composition of rocks under the influence of atmospheric or hydrospheric agencies. Sometimes termed the "decomposition" of rocks and minerals, chemical weathering is better viewed in more conservative terms: The products of chemical weathering must either (a) be formed as a new mineral (synthesis mechanism) or (b)

remain as a residue when other constituents are removed (residue mechanism). Polynov (1937) termed these "products of accumulation" and "ortho-eluvium," respectively, although both are accumulations by different mechanisms. Solutes which pass into the ground water are also "products" of weathering but are of less concern to soil mineral content except as they may re-enter the cycle through synthesis (case 1). Likewise, ions which are released from minerals and temporarily held in adsorbed forms which are available to plants are products of chemical weathering and are of first importance to crop production; however, they are not emphasized in the usual consideration of chemical weathering because their quantities are so small compared to that of the weathered mass.

Decomposition is indeed involved in chemical weathering in the release of reactants for the synthesis mechanism; likewise, decomposition of a more readily weatherable substance and its complete removal in solution are necessary for the operation of the residue mechanism. However, the products of chemical weathering (aside from solutes in ground water) are in either case something other than a "decomposed" substance. The use of such terms as "decomposition" (Merrill, 1906) and "katamorphism" (Van Hise, 1904) grew out of the fact that the products of chemical weathering were formed or left behind from decomposition of something else and were frequently colloidal. Mineralochemical analysis had not developed to the point that the products formed could be determined as new minerals, and this aspect was not emphasized in early literature as it came to be later.

The province of chemical weathering is, therefore, the formation or residual accumulation of minerals as a function of their relative stability to the chemical weathering processes (Sections II and III); it includes the frequency distribution of minerals in soils (Section IV) and the rate of weathering release of nutrient elements from soil minerals (Section V).

c. Weathering Akin to Deuteric and Hydrothermal Alteration of Minerals. The layer silicates and other minerals frequently encountered in weathering studies are also formed by deuteric and hydrothermal alteration. Consequently, these layer silicates occur in the geologic column at much greater depths than the depths of initiation of weathering. Although these layer silicates enter soils when the rock formation is exposed at the surface by erosion, these mineral species in such soils do not reflect chemical weathering, except by their relative resistance to weathering subsequent to exposure.

Deuteric alterations occur late in the crystallization of rocks (Bowen, 1922). In gabbro, for example, the alkali- and silica-rich interstitial

solutions react with the olivine, pyroxene, and amphibole, which typically crystallize out earlier, to form Mg-rich layer silicates such as chlorites and serpentines. They also react with feldspars to form sericite. The complex mixture can be seen in the rock by means of a microscope. Similarly, in the metamorphosis of rocks, chlorite may form from garnet-biotite shist and sericite from feldspars (Harker, 1932).

The term "hydrothermal alterations," following the usage of Shand (1944), refers to the changes in rocks resulting from the movement of hot solutions along well-defined channels or fractures within the earth. A few examples of hydrothermal alteration are given to show the close relation of this type of change to weathering. A quartz monzonite was hydrothermally altered (Sales and Meyer, 1950) to sericite for 20 feet from the fracture through which the hydrothermal solution circulated. The potassium was furnished from orthoclase. An isothermal front in the 300–400° C. range is suggested as defining the limit of sericitization. The next 20 feet were altered to kaolinite, with the orthoclase being unaffected. The next 30–60 feet were altered to montmorillonite. Gradation followed through chloritized rock biotite to the unaltered rock. The degree of alteration thus varied with the distance from the hot solutions in the fracture. The rock alteration described above was clearly caused by solutions moving deep within the earth; yet, there are examples of similar alterations caused by hot solutions near the surface (Schmitt, 1950). At Yellowstone Park, hot spring waters have converted volcanic rocks to rocks containing beidellite and kaolinite, quartz and orthoclase, and zeolites and calcite. The alterations there differ from the deeper types in that most of the water involved is of meteoric origin warmed by superheated steam from depth. It is thus a type of surface alteration activated by a deep-seated heat source.

The layer silicates formed by alteration enter soils when the rocks are exposed at the surface, but these layer silicate species in no way reflect the climate in which the soil was formed. These examples are cited as illustrative of the numerous occurrences in relatively young soils of minerals of hydrothermal origin, which cannot be related to chemical weathering.

Noll (1936a, 1936b, 1936c) demonstrated hydrothermal synthesis of several layer silicates in the laboratory in the system $Al_2O_3.SiO_2.H_2O$. Kaolinite formed below 400° C., and pyrophyllite was formed above this temperature. With the addition of alkali and alkaline earth metallic ions to the system, kaolinite formed when the metallic ion concentration relative to alumina and silica was low, but montmorillonite was favored by increasing ratios of these metallic cations, particularly that of MgO. As the relative potassium content was raised, sericite was formed and then

feldspar at still higher potassium ratios and higher temperatures. These experiments in the laboratory are of principal interest in the elucidation of alteration mechanisms but may be indicative of chemical weathering mechanisms.

2. *Pedochemical versus Geochemical Weathering*

Viewpoints differ greatly as to the extent to which chemical weathering is identified with soil formation as distinct from parent material formation. The term "pedochemical weathering" is here defined to apply to the chemical weathering which has taken place in the soil during its formation and to that which is taking place in the soil currently. The term "geochemical weathering" is defined to apply to the chemical weathering which is considered to have taken place in the parent material before the start of soil formation (granted that geochemical weathering in a broader sense includes pedochemical weathering also). The general term "chemical weathering" is employed to include both subdivisions without distinction. Although it is not always possible to distinguish which of these two subdivisions of chemical weathering is primarily responsible for the origin of minerals in a given soil, and although the distinction is sometimes a matter of definition of "soil formation," different authors often wish to state a preference of viewpoint, and the use of the two terms as defined is therefore extremely useful for clarity.

That physical weathering is largely completed during soil parent material formation seems to be generally agreed upon. However, some writers regard all chemical weathering as soil formation (pedochemical weathering identical to geochemical weathering), whereas others restrict the definition of soil to the upper portion of the geologic column which is greatly influenced by the biological forces. Holding the latter view, Marbut (1951) stated that "the soil is that layer of the earth's crust lying within the reach of those forces which influence, control, and develop organic life." The geologic material beneath was termed the "soil material" or "soil parent material." It is ordinarily unconsolidated—that is, it is physically weathered. Beneath the soil material is consolidated geologic material. These views presented many years ago are adhered to by most of the soil scientists who followed. Kellogg (1943) discusses weathering under the heading "building materials for soils"; this concurs with Marbut's view of weathering as parent material formation. Physical, chemical, and biological "processes meet and mingle in the surface film of the earth's crust to form the soil which is neither strictly physical nor strictly biological but a combination of both." Likewise, according to Robinson (1949, p. 60), ". . . it is desirable to bear strictly in mind the distinction between weathering, which produces the

material from which the soil is developed, and pedogenesis, which results in the development of a soil profile.'' As will be brought out subsequently, chemical weathering has had the major part in producing the colloidal minerals present in soils and thus the properties of soils, regardless of whether it is considered to be largely pedochemical or geochemical.

a. Situations of Minimal Pedochemical Weathering. When the definition of soil is restricted to that portion of the geologic column upon which biological forces are acting, many soils have developed with little pedochemical weathering of minerals. The test of little pedochemical weathering under this restriction is that the mineral content of the solum be similar to that of the C horizon.

In general, chemical weathering of minerals is slow relative to the time required for an unconsolidated material to be called soil. As soon as biological forces have taken hold on a fresh alluvium, an azonal soil is recognized; but the mineral weathering stage (Jackson *et al.*, 1948) is that of the soil or rock column from which the alluvium was derived. The same applies to young soils (Regosols) on till, loess, or other unconsolidated deposits. In these cases, pedochemical weathering is minimal. The accumulation of organic matter and other effects of biological activity, quite apart from weathering, are recognized as initiating soil formation.

Highly weathered geologic columns present a similar situation of minimal pedochemical weathering, if the term ''soil'' is restricted to that portion of the geologic column upon which biologic forces have acted. The main chemical weathering has, under this restriction, occurred in the soil parent material formation, as forcefully advocated by Nikiforoff (1949). The test of pedochemical weathering under this restriction is that mineral content in the solum differ from that in the immediately underlying parent material. In the Low Humic Latosols of Hawaii (unpublished data of the authors and associates) there appears to be little mineral weathering change within the range of biological forces or immediately beneath. Pedochemical weathering is minimal, even though the weathering stage is advanced. Deep in the column, the geochemical weathering profile shows a transition from kaolin to basaltic rock, at about 25 feet.

Mineral analyses of the A and B horizons of several soils of intermediate weathering (Coleman and Jackson, 1946) showed similarity to those of C horizons, and thus illustrate minimal pedochemical weathering in soils of intermediate weathering stages. The occurrence of sodium-rich feldspars, quartz, muscovite, and even some biotite in weathered rock of Switzerland led Niggli (1926) to the conclusion that the chemistry of the soil was similar to that of the parent rock.

b. Situations in Which Pedochemical Weathering Is Clearly Evident. Situations in which pedochemical weathering is clearly evident include the following:

1. Release of cations and anions from minerals in the soil, including those taken up by plants and those lost by leaching.
2. Pedochemical deposition of sesquioxides and layer silicates ("clay formation") in the B horizons.
3. Pedochemical accumulation of sesquioxide and titaniferous surface horizons and crusts.
4. Coincidence of the depth of chemical weathering with the depth of biological activity and soil development.

The importance of pedochemical weathering in situation (1) both in soil formation and in practical agriculture is clearly evident and is discussed further in Section V. Ionic release is the first step in weathering reactions which lead to new weathering products.

To the extent that new minerals colloids are formed and accumulate in the B horizon, situation (2) arises. The occurrences of the orterde and ortstein of the Podzol and the clay accumulation in the B horizon in the Gray-Brown Podzolic, Brown, and Planosol groups seem clearly to represent mineral colloid formation by pedochemical weathering, in addition to varying amounts of illuviation and residual accumulations. Smith (1942) concludes that the development of soils from loess in Illinois "is toward the condition of a claypan soil, or Planosol." Whiteside and Marshall (1944) concluded that clay formation and its distribution within the profile have been the chief result of soil formation in the Putnam and Cowden soils (Planosols) of Missouri and Illinois. Allen (1930) and Bray (1935) have described firm evidence of illuviation of a colloidal montmorin series mineral (beidellite-nontronite) which "fills cracks and cavities and has the cleavage plates oriented parallel to sides of the deposit" (Allen, 1930). "The downward movement through cracks and channels, as a result of water action, of discrete particles" was observed by Bray (1935). Bray in unpublished work (personal communication) states that the same deposition of clay was observed in worm holes. These observations support the concept of claypan formation by illuviation, as distinguished from clay formation by weathering in place. Yet the formation of some montmorin series minerals by weathering is suggested by the quantitative relationships, since there is an increase with time in total quantity of montmorin in the profile (Bray, 1934). Bray (1937a, 1937b) concludes that weathering of micas produces the expanding layer silicates and finally minerals of more advanced ("lateritic") stages, as indicated by the silica-sesquioxide ratios.

Accumulations of surface horizons and crusts in the form of ferruginous and titaniferous materials, situation (3), seem clearly to be the result of pedochemical weathering in the Humic Ferruginous Latosols (Sherman *et al.,* 1949a). Numerous similar examples undoubtedly occur.

In situation (4), geochemical weathering has not kept ahead of soil formation and/or erosion. To the normal processes of geochemical weathing have been added the biological and other processes peculiar to soils. When the weathering is shallower than biological forces normally extend, the soil is termed a Lithosol. When soils form on bare rocks, the inception of soil formation is recognized when lichens or other low forms of life begin to grow. As weathering loosens up some debris on the surfaces of rocks and weathering of some mineral constituents sets in, the weathering is coincident with soil formation.

The coincidence of the depth of rock weathering with soil formation arouses the interest of soil scientists in chemical weathering, because the soil can form only because of the vast changes in rocks wrought by chemical weathering. Thus Jenny (1941) includes weathering as part of soil formation, while recognizing that many soil scientists sharply distinguish weathering from soil formation. Haseman and Marshall (1945) state that a deeper soil layer than that just below the B horizon must be used to obtain the basal Zr content for calculation of the soil volume changes resulting from weathering. This further illustrates that the geochemical weathering profile may be deeper than the solum and the soil profile as usually defined.

It should be pointed out that chemical weathering in situation (4) is no more fundamental than, and often is little different from, that occurring in deeper columns beyond the solum. It is therefore not surprising to find a number of soil scientists who prefer to extend their definition of soil to include *all* weathered zones, a viewpoint set forth by Bushnell (1944, 1950, 1951) and employed in deep profiles studied by Weaver *et al.* (1949).

c. Chemical Weathering Important in Determining Soil Colloids. From the examples given, both those in which pedochemical weathering is minimal and those in which it is clearly evident, it is uniformly apparent that chemical weathering is largely the avenue by which the colloidal minerals of soils are supplied. As already mentioned, deuteric and hydrothermal alteration supplies some of the colloidal minerals to soils. It is also evident that the minerals of coarser sizes persist in soils after more easily weathered ones are removed by chemical weathering. It is not critical for our present review whether the definition of soil includés the entire weathering profile (geochemical plus pedochemical) or not. The degree of chemical weathering and the processes of

it remain the same, whether classified (a) as being geochemical, i.e., occurring in the parent material (Kellogg, 1943; Nikiforoff, 1949; Marbut, 1951), or (b) as being pedochemical, i.e., occurring in the soil profile, however deep (Jenny, 1941; Bushnell, 1944, 1951; Haseman and Marshall, 1945; Weaver *et al.,* 1949). In either case, chemical weathering of minerals somewhere, not necessarily in their present site, for the most part determines the nature of the minerals present in soil colloids. If it is held that most of the chemical weathering occurs in the parent material formation, case (a), rather than in soil formation, then the attendant conclusion must be accepted that the mineralogy of soil colloids (and many important soil properties, both chemical and physical) is determined to like extent by the parent material.

3. Terminology for Weathering Products

The term "clay fraction" will include the particles less than 2 μ in equivalent diameter, whereas the term "mineral colloid" will refer to the finer clay fractions, including particles less than 0.2, 0.1, 0.08, etc., μ in diameter, according to the individual report. The term "clay mineral" refers to minerals in the clay fraction, including both layer and other silicates and feralitic clay minerals. In the interest of preciseness and clarity, the term "layer silicate" is employed for that structural group of silicates.

Because colloidal layer silicates are universally involved in a consideration of the results of chemical weathering, passing reference will be made to the extensive reviews available on their structure and nomenclature. Modern concepts of the layer silicates minerals (those silicates with closely knit layer units of crystal structure) have been reviewed in detail by Grim (1942), Ross and Kerr (1931), Ross and Hendricks (1945), and Gieseking (1949). The nomenclatural and broad structural relationships of layer silicates to other silicates are reviewed by Jackson *et al.* (1949), and details of layer silicate structures and properties are reviewed in detail by Marshall (1949) and Brindley (1951). These topics will therefore be excluded from present consideration.

In agreement with Ross and Kerr (1931), the term "kaolin" will be employed as a general name for the 1:1 family of layer silicates, including kaolinite, halloysite, and their hydrates and polymorphic relatives. Following the reasoning of Correns (1950, 1951), the term "montmorin" is employed to include the isomorphous series of 2:1 layer silicates, including montmorillonite, beidellite, saponite, nontronite, and other isomorphous relatives, all having the property of expansion to approximately 18 A. in the presence of glycerol. The terms "montmorin," "montmorin series," and "montmorin isomorphous series" have iden-

tical meaning. The term "montmorillinoid" has been employed for this meaning also, but it is not given preference because of the connotation generally given in mineralogy to the "oid" suffix as meaning atypical or not typical of the mineral series, family, or group to which it is attached (Hseung and Jackson, 1952). For example, feldspathoid means feldspar which is not typical though related in some characteristics; it does not mean an isomorphous series of feldspars. Likewise, amphiboloid is not typical of the amphiboles, nor chloritoids of the chlorites. As pointed out by Correns, the term "montmorin" is short, convenient, and parallel in construction to kaolin. Because the montmorin crystal structural relationships are those of an isomorphous series, whereas those of the kaolins are those of a family (Jackson *et al.*, 1949), the formal terms are "montmorin series" and "kaolin family." The short versions "montmorin" and "kaolin" are quite clear and are commonly used. The name "montmorillonite" is thus reserved for, and used as, a mineral name in the usual sense.

II. Relative Stability of Minerals; Weathering Sequences and Indexes

When a mixture of minerals deposited together in one rock formation is subjected to the agencies of chemical weathering, some minerals are weathered faster than others. A list of minerals according to their relative stability to weathering is designated a "weathering sequence." The fundamental basis of establishment of a weathering sequence lies with one or more of the following criteria: relative persistence with age of formation, geographic correlation with weathering intensity factors, particle-size (specific surface) function, and persistence as a function of depth in the formation, as will be discussed in Section III, 1.

To make use of mineralogical analyses of soils (Section IV) in the estimation of the inherent fertility of soils (Section V), the relative stability of the mineral species present must be known. The weathering sequences or relative stability series to be considered in this section are the yardsticks by which the mineralogy of given soils may be interpreted (a) in terms of degree of weathering represented and (b) in terms of inherent productivity and fertility needs. Means are at hand of condensing the data on mineralogical analysis into index numbers, called weathering indexes, which are useful for both purposes (a) and (b).

1. *Mineral Weathering Sequences*

Different weathering sequences of minerals have been worked out for different categories of minerals. Weathering sequences have been worked

out for minerals of heavy specific gravity, coarse-grained minerals, colloidal minerals, and combinations of these categories.

a. Weathering Sequence of Heavy Minerals. Of the minerals of heavy specific gravity, the less stable were found to occur in decreasing amounts in rocks of increasing age (Pettijohn, 1941). Thus olivine was not found in rocks older than Pleistocene; augite is rare or unknown in rocks of pre-Cambrian age but becomes increasingly common in younger rocks. Pettijohn's weathering sequence (most stable mineral first) follows: (−3) anatase, (−2) muscovite, (−1) rutile, (1) zircon, (2) tourmaline, (3) monazite, (4) garnet, (5) biotite, (6) apatite, (7) ilmenite, (8) magnetite, (9) staurolite, (10) kyanite, (11) epidote, (12) hornblende, (13) andalusite, (14) topaz, (15) sphene, (16) zoisite, (17) augite, (18) sillimanite, (1919) hypersthene, (20) diopside, (21) actinolite, and (22) olivine. The first three minerals were assigned negative numbers to indicate their tendency to formation rather than disappearance during long periods of burial.

Longstaff and Graham (1951) found hornblende to be more stable than olivine. This discrepancy from Pettijohn's sequence may be a result of the different properties of the many hornblendes found in nature. A grouping of heavy minerals in four categories of stability is suggested by Weyl (1952):

Extremely unstable: Olivine, hornblende, augite.
Slightly stable: Garnet, epidote.
Stable: Staurolite, kyanite, sillimanite, andalusite.
Very stable: Tourmaline, zircon, rutile, titanite, magnetite.

Determination of total zirconium was reported by Marshall and Haseman (1943) to be a satisfactory method for estimation of zircon, the most resistant of the heavy minerals. As is indicated by Pettijohn's sequence given above, zircon should be the most appropriate reference mineral (rather than alumina, commonly employed) from which to calculate the chemical weathering losses of materials. Calculations of this type based on zirconium are made for a number of soil profiles by Haseman and Marshall (1945).

Buckhannan and Ham (1942) found that epidote, augite, hornblende, and kyanite had disappeared from soils on old (Permian) materials and had largely disappeared from old alluvium but were common in the soils on Tertiary and Pleistocene materials in Oklahoma. This study illustrates the way in which the relative stability of heavy minerals can be employed to establish the age of the rock formation from which soils are derived. Carroll (1944) concluded that heavy minerals (specific gravity of 2.9 and over) in the sand fraction of soils give a useful means of identifying parent rock formations for a number of west Australian soils.

b. Weathering Sequence of Coarse-Grained Minerals. To the extent that the susceptibility to weathering of a mineral overshadows specific surface, a weathering sequence can be defined strictly in terms of mineral species without reference to their particle size. As an extreme case, gypsum is moderately soluble and is thus easily removed by leaching; consequently, no attention need be paid to the crystal size in rating its susceptibility to weathering.

Goldich (1938) presented a branched stability series of coarse-grained minerals (most stable last):

mafic	*feldspathic*
olivine	calcic plagioclase
augite	calci-alkalic plagioclase
hornblende	alkali-calcic plagioclase
biotite	alkalic plagioclase

potassium feldspar
muscovite
quartz

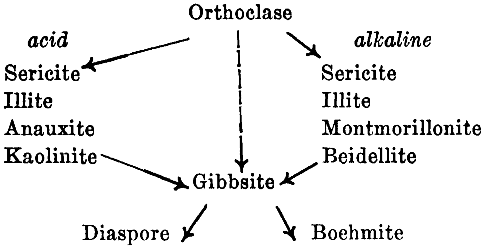
This sequence is similar to the Bowen (1922) sequence for temperature of crystallization (olivine, 1890° C. grading to quartz at 570° C.), a fact that has been interpreted as reflecting the increasing instability of minerals with the increasing departure of the temperature from that of the environment of formation.

Marel (1947, 1948a, 1949) has made extensive observations on the relative stability of magmatic minerals, when weathering conditions and particle size are kept equal, and has summarized his observations (personal communication) in the following weathering sequence (most resistant last): basic volcanic glass, olivine, hypersthene, biotite, augite, amphibole, anorthite, epidote, bytownite, andesine, oligoclase, muscovite, garnet, orthoclase, microcline, albite, allanite, zircon, staurolite, rutile, tourmaline, and quartz. He summarizes: "The most resistant of the minerals accumulate, so that . . . the weathering state of the soil, e.g. the power of a soil to supply nutrient elements to the plant" can be characterized, as will be further considered in Section V. Marel (1947) found that rhyolitic tuff contained 42 per cent of amphibole in the heavy fraction, the slightly weathered material contained 32 per cent, the moderately weathered contained 14 per cent, the strongly weathered 5 per cent and the very strongly weathered revealed 0 per cent of amphiboles. In this same investigation, the resistant mineral zircon increased from 6 per cent in the heavy fraction of rhyolitic tuff to 40 per cent in the very strongly weathered sample.

Quartz is listed as the most stable mineral in the two sequences just given because coarse-grained quartz is extremely resistant to weathering.

Humbert and Marshall (1943) have shown how quartz grains can be weathered by iron-oxide crystal growth in cracks. Engelhardt (1937) similarly noted sharp-angled (fractured) quartz grains in the finer fraction and rounded grains in the coarse. Quartz particles of clay size have a lower relative stability, as will be brought out in the weathering sequence for clay-size particles.

A sequence of orthoclase weathering in acid and alkaline environments is given by S. A. Tyler of the University of Wisconsin in his lectures:



The broken arrow was inserted by the writers to represent the accumulation of gibbsite crusts on weathered rocks (Alexander *et al.*, 1942).

A weathering sequence of both light and heavy minerals, referring largely to coarser-size particles of the silt, has been worked out by Graham (1940, 1950, and personal communication) on the basis of reactions of the minerals with H-clay as follows:

Least stable: Olivine, apatite, anorthite, and bytownite.

Moderately stable: Biotite, augite, hornblende, garnet, epidote, labradorite, and andesine.

Stable: Staurolite, orthoclase, microcline, albite, and oligoclase.

Most stable: Quartz, muscovite, zircon, tourmaline, rutile, ilmenite, anatase, kyanite, titanite (sphene), and magnetite.

Vanderford (1942) studied the changes in quartz and calcium content of the silt in seven locations extending from northeastern Iowa to central Mississippi, and found that the quartz content increased from about 60 to about 80 per cent as the temperature and rainfall increased from the northerly to the southerly location. The calcium content decreased from about 80 to about 60 meq. per 100 g. in the same traverse. Quartz and calcium in the silt thus appear to be a moderately sensitive measure of degree of weathering within the temperate zone. The difference can be explained by the weathering away of plagioclase in accordance with the relative stability sequences given above.

Springer (1949) showed that the ratio of K : Ca in the silt was 0.3 greater in the A horizon than in the underlying loess, which indicated

relatively more weathering of calcium than of potassium minerals in the A horizon. He also concluded that the quartz: Ca ratio is a sensitive measure of the degree of weathering of loessial materials. Younger and thicker loess contains more feldspars and other easily decomposed minerals than thinner and older loess occurring along the Mississippi River, according to Wascher *et al.* (1948).

c. Weathering Sequence of Clay-Size Mineral Particles. With increasing fineness of mineral particles, the mineral stability sequence is somewhat different from that of coarse-grained mineral particles because specific surface becomes great enough to hasten weathering of minerals which are more stable in coarser sizes. By clay-size mineral particles is meant mainly mineral particles less than 2μ in diameter, but the sequence applies to some extent to the size range of 2–5μ (fine silt-size particles) also. The mineral weathering sequence of Jackson *et al.* (1948, 1952), consisting of thirteen stages for fine particles (most stable stage given last), follows: (1) gypsum (also halite, sodium nitrate, ammonium chloride, etc.); (2) calcite (also dolomite, aragonite, apatite, etc.); (3) olivine–hornblende (also pyroxenes, diopside, etc.); (4) biotite (also glauconite, magnesium chlorite, antigorite, nontronite, etc.); (5) albite (also anorthite, stilbite, microcline, orthoclase, etc.); (6) quartz (also cristobalite, etc.); (7) muscovite (also 10-A. zones of sericite, illite, etc.); (8) interstratified 2:1 layer silicates and vermiculite (including partially expanded hydrous micas, randomly interstratified 2:1 layer silicates with no basal spacings, and regularly interstratified 2:1 layer silicates); (9) montmorillonite (also beidellite, saponite, etc.); (10) kaolinite (also halloysite, etc.); (11) gibbsite (also boehmite, allophane, etc.); (12) hematite (also goethite, limonite, etc.); and (13) anatase (also zircon, rutile, ilmenite, leucoxene, corundum, etc.).

Included in the above list are slight changes from the original, including the inclusion of apatite at stage 2; the substitution (Jackson *et al.*, 1952) of interstratification and vermiculite terminology for "mica intermediates" in stage 8; the assignment of allophane to stage 11 (Tamura *et al.*, 1953); and the inclusion of zircon (Marshall and Haseman, 1943; Marel, 1947) and leucoxene (Tyler and Marsden, 1938; Carroll and Woof, 1951) in stage 13. Vermiculite in quantities sufficient to give a distinct 14-A. spacing was given (Hseung and Jackson, 1952) the weight 8.5 in the weathering mean calculation, Section II, 2c.

Kelley *et al.* (1939a) reported chlorite in the colloid of a California soil, and later Jeffries and Yearick (1949) reported chlorite in the clay fraction of several Pennsylvania soils. Stephen (1952a) reported chlorite in soils of the Malvern Hills of England and attributed its origin to weathering of basic rocks (high in hornblende, biotite, etc.). The weath-

ering sequence suggested by Stephen (1952b) was from these ferromagnesian minerals to chlorite, and then to vermiculite, in accordance with the weathering sequence given in the previous paragraph (Jackson *et al.*, 1948, 1952). However, occurrence of a pedogenic chlorite formed in a weathering sequence following mica-vermiculite has been proposed by Jeffries *et al.* (1953). This indicates the possible occurrence of pedogenic chlorite in several positions in the 2:1 layer silicate stages (stages 4, 7 through 9) according to its composition. Caillere *et al.* (1947) reported formation of a 14-A. stable diffraction spacing as a result of treatment of a montmorin with $MgCl_2$. Thus one might expect the occurrence of an aluminous chlorite (from mica layers), in a regime of high magnesium such as with biotite weathering, in the same weathering stage as montmorillonite. At the same time ferromagnesian chlorite of rocks, listed in the previous paragraph, has stage 4 stability. Chlorites of intermediate composition would be expected to have stabilities intermediate between stages 4 and 9. L. D. Whittig and the senior author have found chlorite interstratified with biotite in weathered coarse silt of a Wisconsin soil.

2. *Weathering Indexes*

Weathering indexes refer to the numbers which express the degree of chemical weathering of a mineral or soil material. The indexes condense the data of mineralogical analysis and assist in its interpretation, both in terms of weathering processes and in terms of probable fertilizer needs of soils. Several types of indexes are summarized here but undoubtedly many more have been employed.

a. Molar Ratios. Ratios of moles of different constituents of rocks, minerals, and soils were employed to condense elemental analyses of these materials (Harrassowitz, 1926; Jenny, 1931; Marbut, 1935). The use of such ratios was an important way of evaluating the relative rates of loss of the different elements during the course of weathering, as clearly summarized by Jenny (1941). These ratios were emphasized to a greater extent before methods of mineralogical analysis of colloids and the weathering sequence of colloidal mineral species were developed.

The chief molar ratios that have been employed are as follows:

$$\frac{SiO_2}{Al_2O_3} = \text{silica : alumina ratio, } sa$$

$$\frac{SiO_2}{Fe_2O_3} = \text{silica : ferric oxide ratio, } sf$$

$$\frac{SiO_2}{Al_2O_3+Fe_2O_3} = \text{silica : sesquioxide ratio, } ss$$

$$\frac{K_2O+Na_2O+CaO}{Al_2O_3} = \text{bases : alumina ratio, } ba$$

$$\frac{K_2O+Na_2O}{Al_2O_3} = \text{alkali : alumina ratio, } ba_1$$

$$\frac{CaO+MgO}{Al_2O_3} = \text{alkaline earth : alumina ratio, } ba_2$$

$$\frac{Al_2O_3}{Fe_2O_3} = \text{alumina : ferric ratio, } af$$

$$\frac{CaO}{MgO} = \text{calcic : magnesic ratio, } cm$$

$$\frac{K_2O}{Na_2O} = \text{potassic : sodic ratio, } ps$$

Alumina has often been employed as the basis for calculation of relative weathering losses of other constituents; hence, the above ratios to alumina serve as measures of depletion of the other constituents. Jenny (1931) employed the ratio of $K_2O : Na_2O$ as a measure of degree of weathering, since sodium is lost by weathering at a higher rate than potassium. The ''shifting value'' is this ratio for the original rock subtracted from the ratio for the weathered product (Robinson, 1949). Also, Jenny (1931) proposed the beta value which is the ratio

$$\frac{ba_1 \text{ of leached horizon}}{ba_1 \text{ of the parent material}}$$

Reiche (1943, 1950) formulated a more complex and inclusive measure of the degree of weathering of rocks based on molar ratios. He plotted ''weathering potential'' defined as

$$\frac{100 \times \text{moles } (CaO + Na_2O + MgO + K_2O - H_2O)}{\text{moles (combined } SiO_2 + TiO_2 + Al_2O_3 + Fe_2O_3 + Cr_2O_3 + CaO + Na_2O + MgO + K_2O)}$$

against the ''product index'' defined as

$$\frac{100 \times \text{moles (combined } SiO_2)}{\text{moles (combined } SiO_2 + TiO_2 + R_2O_3)}$$

The consistency in over-all results of the molecular ratios to weathering sequence of colloidal minerals is at once apparent from the shift in elemental composition of the minerals as several stages of the sequence is traversed; this general relationship with respect to the silica: sesquioxide ratio was pointed out at the time of the presentation of the weathering sequence for clay-size minerals (Jackson *et al.*, 1948). The fact that the silica: sesquioxide ratio has little significance among the 2:1 layer silicates (corresponding to stages 6–9 in the sequence) has been pointed out by Marshall (1935) and further by Hseung and Jackson (1952).

Robinson and Richardson (1932) and Robinson (1949) expressed the degree of weathering by the proportion of the total alumina of the soil which was in the clay fraction. They also suggested an index similarly calculated for iron oxide. Layer silicates in clay under this system of evaluation are given the role of the final end product of weathering (that is, a sediment consisting of layer silicate clay and quartz silt would have a weathering index of 100 per cent). Contrary to this role, it is clear from many reports in the literature that layer silicates of clay size continue to weather progressively; thus, micas weather to partially expanding and expanding layer silicates, to kaolin, and to free oxides.

b. Weathering Stages. The term "weathering stage" as applied to the weathering sequence grew out of the common expression "stage of weathering" of rocks. Polynov (1937) defined four stages of weathering and characterized each as a measure of the extent to which weathering has proceeded, as follows:

	Residual material (Ortho-eluvium)	*Formed material*
STAGE I.	coarse detrital material	clastic drifts
STAGE II.	calcareous material	chlorides and sulfates (removed to another site)
STAGE III.	*siallitic* material (alumino silicates)	carbonate (deposited elsewhere)
STAGE IV.	*allitic* material (aluminous compounds)	*siallitic* (allophanic) products

The first stage is recognized as physical weathering and sorting, whereas the other three stages concern chemical weathering. These broad stages of chemical weathering of rocks to form parent materials and soils are universally recognized. The extent to which the aluminosilicates and the aluminous compounds of his stages III and IV are merely residues as opposed to products of the synthesis mechanism and their mineral compositions is not established by Polynov. Polynov did make a contribution in emphasizing a continuity between the various stages of weathering.

It is not yet known the extent to which longer time may offer a counterpart to greater intensity of weathering in arriving at a given stage.

Jackson *et al.* (1948) defined weathering stage in terms of specific minerals associated with a given degree of weathering. It was observed that "three to five minerals . . . are usually present in the colloid of any one soil horizon . . . in the form of a distribution curve, dominated (40 to 60 per cent) by one or two minerals with other minerals of the sequence decreasing in amounts with remoteness in the sequence." When the percentage of minerals present at each stage was plotted against the weathering stage, distribution curves were obtained for many soils ranging along the weathering stage axis. Additional examples of such distribution curves, representative of a Ferruginous Humic Latosol, are shown in Fig 1. Kelley and Dore (1938) had previously noted that one

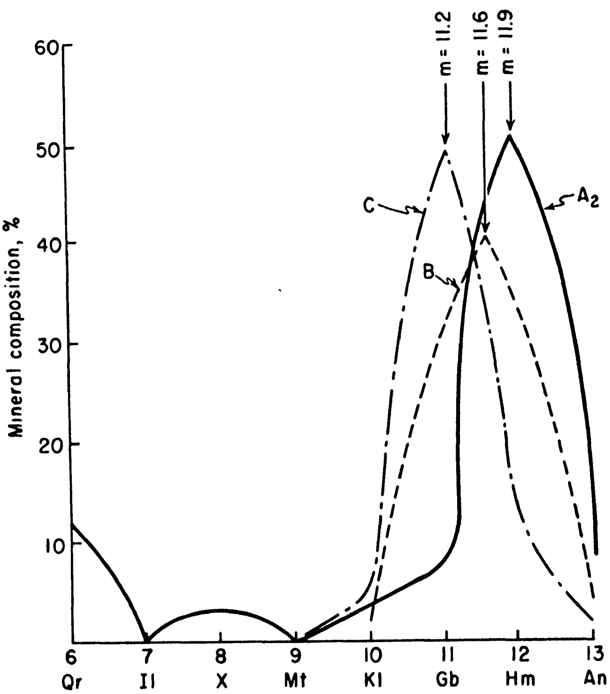


FIG. 1. Mineral distribution curves and weathering mean (m) of the Naiwa soil of the Ferruginous Humic Latosols (from Tamura, 1951).

colloidal mineral generally predominates in any one soil horizon but that several other minerals were generally present in lesser amounts, thus in a way anticipating the occurrence of weathering distribution curves. Dominance of one mineral in a given tropical soil has also been noted.

c. Weathering Mean. The results of chemical weathering are measured both by the residual minerals (residue mechanism) and the solids formed from solution (synthesis mechanism). In soils unsaturated with bases, the stage of weathering can be measured by the clay-size minerals alone, whereas in supersaturated soils the calcite and gypsum must also be included in the calculation in addition to clay-size minerals (Hseung and Jackson, 1952). A mean stage of chemical weathering, termed "weathering mean" (m), is calculated in which p is the percentage of

$$m = \frac{\Sigma(ps)}{\Sigma(p)}$$

a mineral in a soil, and s is the weathering stage of that mineral. The summation (Σ) is the simple addition of the various $p \times s$ values of all the minerals to be considered on a given soil. The weathering mean m has the dimensions of weathering stage (1–13) and is considerably more sensitive to weathering changes than is the silica:sesquioxide ratio (Hseung and Jackson, 1952; Jackson *et al.*, 1948). It is sensitive to changes in layer silicate weathering stage wherein, as pointed out by Marshall (1935), the silica:sesquioxide ratio is not. The weathering mean is used as an index of weathering in different soils and in different horizons of the same soil profile and as a measure of the geochemical weathering of parent materials. Where the silt fraction has been weathered appreciably (especially in Latosols), the weathering mean can also be applied effectively to that fraction.

III. Factors Affecting the Reaction Rates of Chemical Weathering

The reaction rates of chemical weathering are controlled by various intensity and capacity factors operating as a function of time, and different combinations of intensities, capacities, and times of weathering may produce a given degree or stage of weathering. The several factors which affect the reaction rates of chemical weathering may be identified also to a considerable extent with the five factors usually considered to govern soil formation, namely, climate, biotic forces, relief, parent material, and time. But the evidence from research on weathering of soil minerals in relation to the development of soil groups points to a vastly different rate of action and difference in relative importance of the different factors in affecting the two phenomena, weathering and soil formation. To the extent that the two phenomena run along parallel (particularly in the tropics), one is able to consider the two processes

simultaneously; however, when sharp divergences occur (particularly in temperate regions), it is necessary to consider them separately.

For convenience, the factors which affect the rate of chemical weathering reactions are to be considered in more specific categories than the five usually listed as controlling soil formation. For example, the climatic factor is considered in terms of temperature, separately, and of rainfall. The effect of leaching is considered as a single intensity factor whether it is controlled by amount of rainfall, distribution of rainfall, rate of evaporation, relief, or internal drainage. The nature and extent of leaching is all-important in the determination of chemical weathering processes. Oxidation and reduction are considered specifically, whether arising from relief, texture of the material, valence of the ions in the minerals, or other factors.

1. *Methods of Measurement of the Factors Affecting Rate of Chemical Weathering Reactions*

The methods of discovery and measurement of the factors affecting the rate of chemical weathering reactions are to some extent similar to the methods of discovery of the factors affecting soil development, namely, geographic correlation, catenary correlation, particle-size function, and depth function. These four methods operate in a consistent pattern, in as much as exposure to weathering factors of various kinds varies in different geographic and catenary locations, with different specific surfaces of the material, and in different degrees of proximity to the earth (soil) surface.

a. Geographic Correlation. Marbut (1951, p. 17) points out that the primary tool for determination of the effect of different soil-forming factors controlling "the conversion of soil (parent) material into soil . . . (is) *geographic correlation.*" For example, the effect of temperature or rainfall is noted by comparison of maps of these factors to maps of soils. Muckenhirn *et al.* (1949) similarly emphasize isolation of individual factors of soil formation by comparison of soils in different localities having identical sets of factors of formation except for one factor under examination. It was proposed (Jackson *et al.*, 1948) that the effects of intensity and capacity factors controlling chemical weathering reactions can be assessed in a similar way by geographic correlation, and this idea was supported by the consistent indications of the mineral weathering sequence given by geographic correlation, by the particle-size function, and by soil depth function. They state: "The mineralogical composition of soil colloids follows the weathering sequence geographically, in accordance with the geographic distribution of climate, together with time of weathering."

It is generally recognized that there is, in a broad general way, an association of chemical weathering processes and products with major soil formations distributed over the earth. This fact is clearly evident when soils of temperate and tropical zones are compared. Marbut (1951, p. 17) states: ". . . the soil consists of material that has been changed from its original geological condition through the action of the forces operating on the earth's surface, yet we know from the study of soils in various places that the kind of change that has taken place is entirely different in different places on the earth's surface, even though the materials of which they have been made be the same." This statement, like many others of Marbut (1951), indicates that he had mineral weathering as well as other changes in mind. Jackson *et al.* (1948) state: "The (colloidal) mineral composition tends to vary in the great soil groups, being far advanced (stages 11 and 12) in the laterites (Latosols), intermediate (stages 8 and 9) in the Chernozems, less advanced (stages 7 to 9) in the Sierozems, and least advanced (stages 3 to 6) in certain types of young soils, for example, those developed on sediments of the Champlain and Ojibway glacial seas." Hseung and Jackson (1952) show a systematic variation in the mineral composition of the great soil groups of China which fits almost perfectly the weathering sequence of minerals worked out for the broad distribution of minerals of the Western Hemisphere. It needs to be recognized that to the extent that weathering has been geochemical rather than pedochemical, the phrase "soil parent material" frequently needs to be read for "soil" in the papers of Jackson *et al.* (1948) and Hseung and Jackson (1952). This change does not, however, alter the fundamental weathering principle proposed.

The association often found of chemical weathering and minerals present in soil groups arises from the correlation, each separately, of two phenomena with a third, namely, (a) soil formation and (b) chemical weathering with (c) climatic factors. To the extent that the climatic factors have affected to the same degree both chemical weathering and soil development, a correlation is found of minerals present with soil groups. This relationship is accorded the emphasis of formal proposition A:

> To the extent that (a) the stage of chemical weathering of minerals in a material is correlated with climate, and that (b) soil groups are correlated with that same climate, there tends to be (c) an association of colloidal mineral weathering products present with the soil groups.

It is immediately apparent from the limitations in this proposition that the degree of chemical weathering often will *not* be associated with soil groups. Two corollaries to proposition A are noted, whereby the corre-

lation is often lost: under corollary IA, similar soils have different minerals present, and under corollary IIA, different soils have similar minerals present.

> Corollary IA: To the extent that chemical weathering has occurred over longer time, possibly with periods of more intense temperature or rainfall factors than in soil formation, the minerals present will be at a more advanced stage of weathering than expected for the soil formation.

Occurrence of kaolin in sediments from which relatively young soils are formed is an example; this has been noted extensively in Australia and reported in one Gray-Brown Podzolic soil in Iowa (Peterson, 1946a, 1946b).

> Corollary IIA: To the extent that climate and other soil-forming factors produce changes in soil features more rapidly than climate affects the extent of chemical weathering of minerals, there will be similar minerals in different soil groups.

For example, occurrence of similarly weathered 2:1 layer silicate minerals was reported by Warder and Dion (1952) in several zonal and intrazonal great soil groups in the Saskatchewan locality.

b. Catenary Correlation. A powerful factor in the development of different soils within a given locality is the drainage, a factor causing catenary groups of soils (Bushnell, 1944). Variations in chemical weathering might be expected to arise between these catenary groups because of the drainage factor. Association of chemical weathering with relief is thus to be studied by catenary correlation. The general situation in this regard is that major changes of relief and drainage may be correlated with changes in mineral content, whereas smaller changes (still highly important to soil profile and productivity rating) cause little change in the chemical weathering of minerals. Proposition B may be stated:

> To the extent that (a) the stage of chemical weathering of minerals in a material is correlated with drainage and that (b) soil groups are correlated with that same drainage, there should be (c) an association of colloidal mineral weathering products present with the soil groups.

Corresponding corollaries IB and IIB can also be stated for proposition B as for proposition A. Under proposition B, Gill and Sherman (1952) noted montmorin series minerals in poorly drained soils of Hawaii, whereas in nearby uplands, kaolin family minerals were abundant. A similar association had been noted by Nagelschmidt *et al.* (1940) in the "black cotton soils" of India associated with kaolin in the upland. Likewise, Jackson and Hellman (1942) noted high montmorin series minerals

in the B horizon of the poorly drained Fillmore soil of Nebraska, whereas more micaceous 2:1 layer silicates were noted (recent studies in our laboratories) in the nearby uplands; general occurrence of montmorin in poorly drained soils developed from highly basic rocks was reported by Walker (1950) in Scotland.

These examples of different soil mineralogy in poorly drained soils are not intended to indicate that such differences always occur; in general, corollary IIB commonly applies. For example, Warder and Dion (1952) noted that the mineralogy in Solonetz and associated intrazonal soils was similar to that in several zonal soils in the Saskatchewan locality. Kelley *et al.* (1940) noted that the clay minerals of alkali soils were similar to those of normal soils and suggested that they had been inherited from the same parent materials. They suggest that the base status during the mineral formation may have been quite different from the present status. Mica, montmorin, and kaolin were found in varying proportions in various localities of alkali soils. Bidwell and Page (1951) noted great similarity in minerals in Ohio soils in a catena involving great variation in drainage and productivity ratings.

It is well to re-emphasize that in both the geographic and the catenary propositions of correlation and in the two corollary situations without correlation, the colloidal minerals present in soil parent materials and in soils are still the products of chemical weathering, as already stressed in Section I, 2c. Although the minerals present in a soil or soil parent material must certainly be a function of the weathering to which the material has been subjected, that weathering need not necessarily have taken place in its present site or present environment, nor need it necessarily be correlated with present soil formation. Thus the field of chemical weathering of soil minerals involves many aspects which are distinct from the field of soil formation, though the two fields have some aspects in common.

c. Particle-Size Function. Chemical weathering becomes increasingly important relative to physical weathering as the particle size of minerals decreases and specific surface increases—a relationship emphasized by Polynov (1937) and many others. As a result of this relationship, there is a minimum size at which a mineral of a given stability can exist in a given intensity and time of weathering; consequently, the size at which extinction of a given mineral occurs provides a measure of weathering intensity and time of weathering (Jackson *et al.,* 1948). Thus the mineralogical composition of colloids of soils shows an advance in weathering stage with increased fineness of the fraction separated for identification. The minerals which are more resistant to chemical weathering tend to persist in greater quantities in the finer-size fractions. Decreasing size

of particles is the "capacity factor equivalent" to translation to greater intensity and/or time of weathering. In stages 10–13, the minerals kaolin, gibbsite, hematite, and anatase may show crystal growth and occur independently of particle size. However, with extreme fineness, formation of hematite monolayers by weathering proceeds rapidly, and they can be found on almost any colloid formed under good oxidation.

Jackson *et al.* (1948) tabulated the percentages of quartz in soils of different weathering environments to illustrate the size of extinction for that mineral. Under intense weathering the minimum size for quartz particles is about 2μ, whereas the minimum size in temperate climates is on the order of 0.1μ. The decrease in amount is of course an asymtotic function of size, but the extinction is stated for the minimum detectable amount for X-ray diffraction of quartz colloid (about 1 per cent).

The size extinction function of feldspars is similar in nature to that of quartz, except that the size which can exist in a given weathering intensity is approximately tenfold larger. Thus Schlünz (1933–1934) showed 12 per cent of feldspars in the 24- to 60-μ fraction, but only 2.8 per cent in the 2- to 11-μ fraction. Few feldspars occur in the fractions smaller than 2μ in Wisconsin soils, but considerable feldspars occur even in the less than 0.2-μ fractions in less weathered soils, as will be pointed out in Section IV, 1d.

In Norway, biotite showed an extinction function at 10μ, giving way to chlorite and sericite-like products under this diameter; feldspars predominated in the fractions from 2 to 10μ in diameter; and micas predominated in the fractions less than 2μ in diameter (Krogh, 1923; Hougen *et al.*, 1925; Rove, 1926; Goldschmidt and Johnson, 1922; Goldschmidt, 1926). The particles in the smaller than 2-μ fraction had sizes predominantly in the size range of 0.2–0.05μ, according to electron microscope observations (Ackermann, 1948). Engelhardt (1937) pointed out that feldspars occurred in soils of northern Europe only in the silt- or larger-size fractions. Because calcium feldspars weather more rapidly than potassium or sodium feldspars, the feldspar content and species provide a sensitive measure of degree of weathering of a material.

Occurrence of feldspars in fine fractions of soils of the humid tropics can be taken as an indication of youthful soils or of the addition of youthful materials to old soils. The size function of feldspars thus can be employed in many situations in the measurement of the intensity and time of weathering.

Many workers make mineralogical analyses only of the entire clay fraction of soils (particles less than 2μ), and because of the fact that the fine colloidal minerals have low diffraction intensity relative to that

in the coarser minerals, the nature of fine colloids is often overlooked and the content greatly underestimated. Pennington and Jackson (1948) noted the occurrence of a colloidal mineral less than 0.08μ in diameter in Chester soil which was amorphous but which accounted for over half of the exchange capacity of the clay fraction. The whole clay fraction showed only diffraction lines for kaolin, and thus the nature of the most active fraction would have been overlooked without size segregation into fractions. Numerous examples of montmorin in the fine colloid (less than 0.06 or 0.08μ) and of mica in the coarse clay fractions have been observed, in Illinois soils (Bray, 1937a), in soils of the North Central States (Russell and Haddock, 1941; Jackson and Hellman, 1942), and even in a Desert soil (Jackson and Hellman, 1942). Well-organized mica crystals have a size extinction function on the order of 0.1μ. Occurrence of montmorin (18-A. diffraction) in the fine colloid of soils (particles of less than about 0.06–0.1μ in equivalent diameter) has been overlooked in many soils which are dominantly mica-like (illitic) in the coarse clay fraction because of the analysis of the total clay fraction (less than 2μ) in bulk without separation of the truly colloidal part.

d. Weathering Depth Function. As pointed out by Jackson *et al.* (1948), the degree of weathering or weathering stage of colloids of a soil tends to advance with increasing proximity to the surface. The reason is the greater leaching incident to the surface soil. The decrease of weathering stage with depth is most pronounced in shallow weathering profiles in which the soil grades into the bed rock. For example, Humbert and Marshall (1943) show the depth function of quartz (increasing with proximity to the surface) and feldspar (decreasing with proximity to the surface) in two soils, one from diabase and one from granite. In the diabase soil the mica stage of weathering showed a maximum at the 33- and 47-inch depth, decreasing both below and above this depth.

Application of the weathering depth function to study of the sequence of mineral weathering is reported by Shearer and Cole (1939–1940a) and Cole (1940–1941). These authors point out that the process of study is simplified by selection of a parent material consisting predominantly of one mineral, and on which a soil is developed without natural or artificial contamination. A soil developed in the Gingin district of western Australia on the glauconitic sandstone (Cole, 1940–1941) showed a kaolin maximum (stage 10) at the surface, much montmorin (stage 9) in the subsoil, and much glauconite (stages 4–8) in the parent material. A little hematite and goethite (stage 11) occurred in the surface soil. The greensand contained little quartz, but the quartz was concentrated in the coarse fractions of the subsoil and soil. The quartz accumulated with the advanced-stage minerals mainly as coarse particles, in accordance

with the sequence for coarse minerals (Section II, 1b). Cole (1940–1941) stated: "In the weathering of the glauconitic sandstone, the glauconite alters firstly to a clay of the montmorillonite group which later is replaced by clay of the kaolinite group together with free quartz and haemetite and (or) goethite."

Rolfe and Jeffries (1952) also made use of the depth function of weathering in the range from stage 7 (mica) in the lower horizons to stage 8 (vermiculite) in the surface horizon. The Barshad (1951) slow exchange effect was employed, whereby the 14-A. vermiculite spacing was amplified with magnesium saturation and the 10-A. spacing, with potassium saturation. The size function (Section III, 1c) was also utilized, since the occurrence of weathering of mica to vermiculite was followed in either the silt or clay fraction.

Biotite decreases from 42 per cent in the subsoil to 3 per cent at the surface in a Latosol developed from rhyolite in Sumatra (Kiel and Rachmat, 1948). Volcanic glass composed 16 per cent of the C horizon but was mostly decomposed in upper horizons. Quartz and sanidine increased with proximity to the surface (presumably in the coarser fractions). Peterson (1946a) noted that the proportion of kaolin to montmorin increased in the A horizon as compared to the B horizons in soils of older Pleistocene formations, but no depth function was shown in the most recent glacial deposits. This type of depth function was concluded to be slightly more pronounced in Podzolic soils and Planosols (more weathered) than in Prairie soils (less weathered).

Muir (1951) illustrated the depth function in a kaolin soil of Syria. He described a kaolinic soil (stage 10) which was underlain just above the parent basaltic rock with a vermiculite-like material (stage 8) which decreased in amount with proximity to the surface. A further illustration of the depth function, concerning the earlier stages, was reported by Muir (1951) in connection with a Desert-Steppe Brown soil in which $CaCO_3$ increased with depth, ranging from 35 per cent in the surface to 53 per cent at a 30-inch depth. A gypsum (stage 1) zone had developed at the 18-inch depth. In all of the examples given thus far, weathering advanced with proximity to the surface.

Failure to show much change from parent material to the soil mineral colloids has also been reported. Shearer and Cole (1939–1940a) reported uniform occurrence of mica with kaolin in a sandstone soil down to a depth of over 10 feet. Cole (1943) reported little change in kaolin content with depth in several soils of western Australia. Little change in free iron-oxide content was observed with depth where the latter was abundant in the parent material at a depth of 6 feet as well as in the soil.

It was noted that montmorin was abundant in a chalk parent rock (on a carbon-free basis), and this mineral persisted into the overlying soil.

In the more highly weathered soils, the depth function of weathering must be observed in a deeper, geochemical profile, extending much below the root zone. This is illustrated by the mineral composition of the Laterite profile given by Mohr (1944), as follows:

1. Surface horizon—quartz or mottled clay (in some cases lost by erosion).
2. Laterite horizon—indurated layer of iron oxides, cellular or concretionary, with white clay.
3. Bauxite nodules in white clay (kaolin).
4. Spotted white clay—kaolin.
5. Siliceous cemented tuff.
6. Fresh ash.

In the Mohr profile given, the Laterite horizon is an example of weathering stage 12; bauxite, stage 11; and kaolin, stage 10 in a depth sequence corresponding to the weathering sequence of Jackson *et al.* (1948).

Prescott and Pendleton (1952, p. 7) present a diagram of the weathering profile of a weathered rock mass in western Australia after Walther and Whitehouse. The principal features of the profile illustrate the depth function: ferruginous surface horizon (stage 12), mottled subsurface, and pallid zone just above the parent rock. Stephens (1949) emphasizes the occurrence of the ferruginous layer over a kaolin (stage 10) subsurface horizon at a depth of as much as 10 feet below the surface.

Carroll and Woof (1951), studying the clay fraction of a lateritic profile of Inverell, New South Wales, Australia, developed from Tertiary basalt, give data which corroborate the existence of the depth function in this highly weathered profile on a geochemical profile scale. The underlying basalt was composed largely of feldspars, olivine, pyroxene, and zeolites. Samples from the base of the profile (at a depth between 16 and 23 feet) showed a concentration of magnetite and iron-stained clay. Olivine of the parent rock had greatly altered to a brown material, possibly nontronite. Kaolinite (stage 10) was also evident. Succeeding upward in the profile (between 12 and 16 feet) a zone of accumulation of kaolinite was evidenced together with some gibbsite (stage 11) and anatase (stage 13). The 11–12 foot level was largely composed of gibbsite (90 per cent) with a small amount of kaolinite and anatase. Between 10 and 11 feet the principal mineral was gibbsite (37 per cent) with leucoxene (36 per cent). From the 10-foot level to the surface, the gibbsite content progressively increased together with that of hematite (stage 12) and ilmenite (stage 13), but the kaolinite content remained fairly constant. The trend of accumulation of minerals in this soil pro-

file was commensurate with loss of SiO_2, CaO, MgO, Na_2O, and K_2O from the surface, with resultant enrichment of Al_2O_3, Fe_2O_3, and TiO_2.

2. Capacity Factors Controlling Rate of Chemical Weathering Reactions

The capacity factors controlling the rate of chemical weathering reactions are (a) the state of subdivision of the mineral and (b) the inherent nature of the mineral, as contrasted to the intensity factors of weathering to be considered in Section III, 3.

a. Role of Specific Surface. The greater the specific surface of the given mineral, that is, the finer the particle size, the more rapidly it will be affected by the processes of chemical weathering, as emphasized by Merrill (1906), Polynov (1937), and many others. The specific surface increases in inverse proportion to the diameter of particles of a material. It has been shown that the weathering sequences are different for fine sizes of minerals than for the coarse sizes in Section II. One result of the effect of specific surface is the size function of mineral weathering discussed in Section III, 1.

As an example of the surface effect on weathering rate, volcanic ash weathers faster than lava, primarily owing to greater surface area exposed to weathering processes. It is commonly observed in the Hawaiian Islands that soil will form faster on the porous and easily disintegrated "aa" type of lava flow than on the dense "pahoehoe" types of flow. Hardy (1946) has found that the recently added volcanic ash in certain tropical areas forms soil as quickly as or more quickly than, the soil is eroding.

b. Role of Specific Weatherability of Minerals. The rate of chemical weathering depends on the specific nature of a mineral, designed k_m by Jackson *et al.* (1948). The specific nature of the mineral is so important in determining the course and rate of weathering that minerals can be arrayed according to their relative stability; this subject was considered in Section II.

Searle (1923) states, according to Stephens (1949): "The rate of weathering depends chiefly on the nature of the rock (k_m) and (or) the character of the weathering agencies" (intensity factors). Stephens states: "There appears to be no well recognized classification of rocks in terms of their ease of weathering except that basalt is regarded as one of the most easily weatherable rocks, and that slow weathering is associated with high silica content." In terms of specific minerals, gypsum weathers more rapidly than calcite. Ferromagnesian minerals weather faster than feldspars, whereas quartz is more resistant to chemical weath-

ering than feldspars. Potassium feldspar is more resistant than plagioclase (Goldich, 1938).

3. Intensity Factors Controlling Rate of Chemical Weathering Reactions

The intensity factors which control the rate of chemical weathering reactions are: (a) temperature and its complementary control on accumulations of humus; (b) quantity of water and its rate of movement for leaching, controlled by rainfall and internal and external drainage; (c) acidity of the solution and associated percentage saturation of the colloid exchange charge with hydrogen; (d) biotic forces, particularly through recycling of bases and influences on amount and character of organic matter accumulated; and (e) the degree of oxidation and its fluctuation (oxidation-reduction).

Weathering of minerals in the tropics is in general influenced by the same factors as are present in temperate regions. Vageler (1933) in the following statement gives a very definite relationship of the influence of climatic factors on soil formation in temperate and tropical regions: "In the main, the same general laws as to the working of climatic factors on a given parent material hold in the tropics as in the temperate climates: the same heat, light, water and air, are at work in both places. What is materially increased in the tropics as against temperate regions is the intensity of climatic action considered in respect to duration and degree." The tropics do not have a winter season, and thus chemical weathering is active during the entire year, whereas in temperate regions chemical weathering nearly ceases during the cold winter period. In tropical regions the soil temperatures are high during the entire year, and according to Vageler, the higher temperature of the soil increases the rate of chemical reactions from two to four times. In the humid tropical areas, with increased rainfall in addition to the higher temperatures, the rate of chemical decomposition may be increased as much as twenty to thirty times.

a. Temperature Factor. The role of temperature in affecting the rate of weathering reactions is generally recognized, particularly by the disparity of reaction rates in the tropical and the temperate regions. Temperature affects the operation of the other intensity factors such as leaching, hydrolysis, and organic matter accumulation. A beginning has been made in characterizing the temperature factor quantitatively. Stephens (1949) relates the Szymkiewicz (1947) air temperature index (T) shown in the equation

$$T = 2.5^{t/10}$$

in which t is the air temperature in degrees centigrade, to the rate of chemical weathering. Stephens was able to correlate this temperature index (T) for a range of about 2 to over 10 with the weathering of rocks. He states: "It would appear that the criterion determining the presence of red loams is the sum of the effects of the weathering power of climate and the ease of weathering of the parent rock." He further states that the red loams or Latosols "occur over a wide range of climate from temperate to tropical in both the U.S.A. and in Australia." In temperate areas they are restricted in occurrence to the most basic rocks, such as basalt and close relatives. In tropical areas they occupy a much greater proportion of the landscape and occur on a wide variety of parent material, "in fact on all but the most siliceous rocks." They occur on schist and some granites. The relationship of temperature as expressed in the Szymkiewicz index to weathering product and soil associated therewith is summarized in Fig. 2, taken from Stephens (1949). The importance

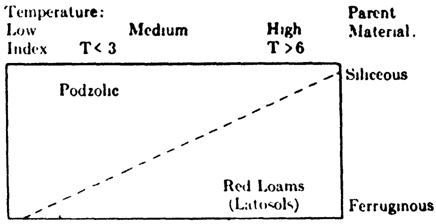


FIG. 2. Diagram showing relationship of occurrence of red loams to temperature, weathering index, and rock character (after Stephens, 1949).

of temperature on rate of chemical weathering is clearly brought out by these observations; latosolization can be accomplished even on acidic rocks if the intensity factor is great enough.

A word of caution is required in the interpretation of the effect of temperature. Proximity to the origin of glaciers has left many temperate zones of northern and central North America, Europe, and Asia with relatively recent deposits of till and loess bearing residues of shales and limestones as well as granite and other igneous rocks, in relatively early stages of weathering. Regions further south and now in warmer climates have had not only the warmer climate but also much longer periods of time in which weathering has had an opportunity to progress. It would be easy to confuse the longer periods of weathering with the simple effect of the difference of temperature now existing. Depth of leaching of $CaCO_3$ increased from 1 to 3 or more meters in the distance from northern to southern Indiana (Weaver *et al.* 1949), but the authors make clear

that the same transect crosses from recent to older till and finally to unglaciated material.

Chemical weathering of minerals is more extensive in regions of cool temperatures (Williams, 1949), even under snow cover, than is often appreciated. Retzer (1949) described extensive formation of mineral colloids in old soils of the Rocky Mountains of central Colorado where cool temperatures prevail.

b. Role of Water and Leaching. Water as an agent in chemical weathering has two distinct roles. In the first place, it is a reactant in the hydrolysis reactions (hydroxylation)–that is, it is a primary source of hydroxyl accumulated in layer silicates and the feralitic hydroxy oxides. These reactions are exothermic. Hydration of minerals causes an increase in volume and is therefore an important factor in decay of coarse-grained igneous rocks (Reiche, 1950). Secondly, water acts as a leaching agent to the extent internal drainage and the supply of water permit its passage through the soil profiles. The two processes, hydroxylation and leaching, are associated to the extent that the soluble products of hydrolysis must be removed to drive the reaction.

Kellogg (1943, p. 32) states: "The chief agent of chemical weathering . . . is water." Byers (1933) expressed the view that weathering is entirely expressible as a hydrolysis reaction, but he noted the influence of temperature, water movement, particle size, and specific nature of minerals on the rate. Marbut (1951, p. 60) states: ". . . the products of rock decomposition invariably contain a higher percentage of combined water than the undecomposed materials." The occurrence of hydroxyl has been made the basis of mineralogical analysis by differential thermal methods (Grim and Rowland, 1942), weight loss (Nutting, 1943), and direct hydroxyl determination (Evans and Jackson, 1952). The concept of the content of combined water and hydration as a measure of weathering has been supplanted by the determination of specific minerals as a function of weathering, as was brought out in Section II.

Leaching drives the chemical weathering reactions by removal of some of the products formed, and in fact leaching of ions may be so extensive that successive stages of weathering involve largely different chemical elements (Jackson *et al.*, 1948). Prescott (1949) has presented a climatic index for the leaching factor in soil formation.

One measure of the leaching factor is the measurement of solutes in river waters of a drainage basin. Smyth (1913) and later Polynov (1937) found the relative ionic mobilities by this sort of measurement to be Ca, Na, Mg, SiO_2, and R_2O_3, in order of decreasing mobility. Goldich (1938) extended the study and reported the order Na, Ca, Mg, K, and SiO_2, in decreasing order of loss. Aluminum was considered to

be neither accumulated or lost, and iron and combined water were gained. Polynov (1937) placed the products of leaching in the four classes (Section II, 2b), and considered successive stages of removal to be separate. The evidence favors simultaneous though preferential leaching mobility (Reiche, 1942, 1950).

Ross and Hendricks (1945) considered leaching rates as the factor determining whether montmorin or kaolin forms in some situations in the southeastern section of the United States. If the alkaline earths and silica are removed quickly, the products of weathering are kaolin and free sesquioxides, whereas if the various constituents are released fast enough to interact before leaching removes part of them, montmorin forms. The nature of the rock or mineral also aids in determining the relative rate of release of the reactants.

Smith (1942) notes that slope influences the proportion of water which enters the profile and in turn determines the extent of profile development. In the Muscatine-Cisne soil sequence, the quantity of montmorin formed in the B horizon appears to be dependent on the quantity of water which infiltrates.

Mohr (1944) has very effectively brought out the importance of internal drainage to the leaching factor and weathering reactions. Drainage controls the movement of water in the soil. He has classified water movement in tropical soils into six simple classes: (a) rapid movement downward, (b) slow movement in a poorly pervious soil, (c) large amount of rainfall on an impervious soil, (d) little rainfall on a very pervious soil, (e) ascent by capillarity from ground water in a poorly pervious soil, and (f) water easily ascending from ground water in a pervious soil. Each one of these conditions has a marked influence on the type of mineral weathering and its products in soils. In (a) kaolinization would be the dominant type of weathering, whereas (c) would be expected to give rise to minerals of the montmorin group.

With the reverse of leaching, that is, with the influx of a large active mass of ionic products, the reactions of chemical weathering are reversible. The occurrence of authigenic micas, feldspars, quartz, zircon, and tourmaline in sediments indicates such a reversal where the ionic constituents are abundant in sea water (Jackson *et al.*, 1948). Dietz (1942) postulated the formation of hydrous micas from montmorin by absorption of K and other solutes from sea water.

c. Role of Acidity. The pH value of a material and the waters passing through it appear to have a marked effect on the rate and nature of chemical weathering. Increasing acidity was assigned a positive sign in the weathering rate function (Jackson *et al.*, 1948). The rapid decomposition of feldspar in the presence of an acid clay was shown by Graham

(1941b). The mechanism appears to be the rapid removal of the metallic cations by the exchange material, at the same time that hydrogen is furnished for hydroxylation of the weathering product. In addition to acid exchange saturation, the effect of the specific acids, such as carbonic and sulfuric, must be considered. A marked release by dilute acids of potassium from soils has been shown (Attoe and Truog, 1946). Depotassication and loss of mica with an increase in vermiculite and kaolinite are greatly accelerated with the advent of leaching in sufficient amounts to bring the soil pH below 7 (Hseung and Jackson, 1952).

Why desilication proceeds at an accelerated rate as acidity increases has been a much debated point. The experimental observation is that kaolinite and gibbsite form under increasingly acid soil conditions, at the expense of minerals of higher silica content. Ross and Hendricks (1945) explain this as a result of the rapid removal of metallic ions and silica by leaching before they could recombine with sesquioxides.

The feldspars are sometimes postulated to weather to sesquioxides in local alkaline regime wherein the silica may be dissolved in alkaline solution. Jackson *et al.* (1948) state that the silica still must leave the weathering zone in an acid solution, since the highest rates of weathering and silica removal appear to be associated with an acid profile. The mobility of silica in acid soils probably may be interpreted as occurring through true solution. Even a soil acidity of pH 4, although "extremely acid" in terms of soil conditions with reference to plant growth, represents only a very slight degree of acidity in the chemical system for insolubilizing silica (Jackson *et al.*, 1948). Marked decrease in the solubility of silica is brought about only by a degree of acidity 4–6 magnitudes more acid than pH 4. Although kaolinite, gibbsite, and boehmite are hydroxyl compounds structurally, they respond chemically more like insoluble weak acids or acid anhydrides, weaker than silicic acid.

d. Role of Biotic Forces. The role of biotic forces in chemical weathering may be summarized under the two headings: (a) ionic uptake cycles and (b) effects of organic residues. Higher plants of course exercise some effect on chemical weathering by their physical action in enlarging cracks in rocks, with the result that waters may enter more readily, and in shading the soil, with attendant effects on soil temperature and evaporation.

Both microorganisms and higher plants hasten the release of nutrients from minerals by the absorption and the exchange of hydrogen ions onto the exchange charges of the minerals. Demolon and Bastisse (1946) considered plants as weathering factors, since in the lysimeter studies they found that more potassium was released from soils on which plants were growing than from bare soils. Accumulated soil acidity is accom-

panied by depotassication of micas (Hseung and Jackson, 1952) and gives rise to the marked need for potassium in the Podzol soil regions. Evidently the depletion of potassium occurs even under natural conditions, since acid Podzol profiles of Wisconsin are low in exchangeable potassium in the state of nature.

Under virgin soil conditions, vegetation returns its nutrients to the surface of the soil as organic residues (Kellogg, 1943). Where the depth to calcium carbonate is within the reach of the roots, the surface soil may be maintained at or near neutrality by this natural return of metallic cations. The process is favored by the naturally high content of bases in grasses (Kellogg, 1943). Trees, particularly conifers, which are low in bases do not recycle enough bases ordinarily to maintain the soil completely neutral throughout the solum (Kellogg, 1943). This situation is reversed in the tension zone between prairie and forest in southern Wisconsin, according to recent observations at the Wisconsin Station. The $CaCO_3$ of the parent material is within reach of hardwood tree roots and is returned to the surface to maintain the A_1 horizon of Miami silt loam at pH 6.8. The Prairie soil occurring on identical material nearby is acid (pH 5.5) at the surface because the $CaCO_3$ has been leached beyond the reach of the grass roots. Thus, in the more acid Podzols, one might surmise that an important reason for great weathering losses of bases is a result of little recycling of bases.

The residual organic matter accumulated on the soil surface has a marked effect on the weathering of minerals, either through effects on leaching of bases and/or through distribution of iron and aluminum oxides in soil. For example, ferns found in the humid tropical regions of Hawaii lay down a very acid forest floor, having reactions of pH 3.5–4.0 (Sherman and Kanehiro, 1948), which is comparable to forest floors of the white pine forests of the cool temperate zone. However, owing to the higher temperatures and conditions favoring oxidation, there is no evidence of podzolization under this acid floor. Nevertheless, the chemical composition of the organic matter added to the soil influences the rate of loss of bases and consequently the rate of chemical weathering of the minerals. Weathering under a very acid forest floor is much faster than under a neutral or alkaline forest floor.

Certain types of organic matter, particularly organic acids, form complexes with the sesquioxide ions and move them from the upper horizon to the subsoil, and to some extent out into the ground water. The result is the typical bleached horizon of the Podzol and the gray appearance of the upper horizon of the podzolic soils. Removal of iron from ferromagnesian minerals is undoubtedly hastened by this action.

A striking demonstration of the biotic effect on sesquioxide accumu-

lation is presented by a mor-forming tree (*Podocarpus sp.*) in New Zealand, under which podzolization occurs in an area otherwise occupied by Latosols (N. H. Taylor, personal communication). Podzols are distributed as "islands" under individual trees. This occurrence amply illustrates the independence biotic forces may have. The weathering index of Robinson and Richardson (1932) for the podzolized material is found to be but 10 per cent, showing the youth of the rock weathering. The weathering mean of Hseung and Jackson (1952) would be affected by the removal of the iron oxides (stage 12) from the A horizon and their deposition in the lower B horizon.

The role of vegetal canopy is important in the tropical regions (Vageler, 1933; Mohr, 1944). Mohr (1944) pointed out that the temperature of air over the soil is markedly lower under a canopy forest. Likewise, the soil covered by forest may be 10–15° C. lower than the soil would be without forest cover. The lower temperature slows down all chemical reactions. The decomposition of organic matter is slower, resulting in an accumulation of organic materials at or in the surface horizon. There is a marked difference in the conditions under the evergreen tropical forest and deciduous tropical forest. Griffith and Gupta (1947) have shown that if teak is planted on Laterite soils, a Laterite crust forms owing to the dehydration of the soil during the drouth period or the dormant leafless stage. The formation of the Laterite crust resulted in poor growth of the trees. This finding has been verified by Sherman *et al.* (1953) in the Hawaiian Islands. These workers have found that when a soil lost its vegetative cover, a crust formed as a result of dehydration. The total volatile matter in dehydrated crust was as low as 3 per cent.

e. Role of Oxidation and Reduction. Oxidation and reduction reactions are instrumental in promoting chemical weathering. Oxidation was assigned a positive sign in weathering equations by Jackson *et al.* (1948). Thus, occurrence of iron in the ferrous state or conditions favoring its reduction promoted montmorin formation (intermediate weathering stage) (Ross and Hendricks, 1945), whereas ferric iron in the mineral or strongly oxidizing conditions resulted in formation of kaolin and free oxides (more advanced stages of weathering). Accumulation of free oxide crusts of the surface is favored by the prevalence through some seasons of the year of oxidizing conditions (Sherman, 1949). Prevalence of reduction causes reversal of the trend toward advancement of the stage of weathering: that is, minerals such as hematite and anatase of the advanced stages are removed with the accumulation of earlier stage minerals (Sherman, 1952a). The proportion of wet and dry seasons and associated degree of drainage and oxidation determines the degree of

accumulation of oxides of manganese as well as iron in Hawaii (Sherman and Kanehiro, unpublished).

A special role of oxidation in weathering was observed by Humbert and Marshall (1943); formation of ferric oxide in cracks of quartz grains was observed to fracture the crystals of quartz. The rate of oxidation also affects weathering through its effect on organic matter accumulation, as brought out in the previous section.

4. *Time Factor in Chemical Weathering*

Time of chemical weathering is obviously complementary to some extent with the intensity and capacity factors which control rate of weathering. Smith (1942) noted that: "On every topographic situation where one finds a Prairie soil in the youngest catena (Muscatine), one finds a Planosol in the oldest catena (Cisne)." Considerably more weathering has apparently taken place in the latter soil, and time has been largely the factor responsible for the increase in weathering.

Jackson *et al.* (1948) state that for a given mineral species and a given particle-size range (constant capacity factors), the weathering stage of the weathering colloid is a product of the intensity functions multiplied by the time during which weathering has been occurring, or simply as "intensity × time" product. Procession through various mineral weathering stages of the sequence follows increase of this product. This relationship is clearly evident in Stephens's (1949) observations, summarized in Fig. 2.

Thorp (1944) points out that some mountain soils show considerable weathering and soil development, where the processes have gone on for sufficient time. On gentle slopes in the Rocky Mountains "time is sufficient . . . for the development of both zonal soils and of the so-called 'over-developed' intrazonal soils." Both B horizon development and lime accumulations are mentioned. The mineral species are not mentioned, but colloid formation by weathering is clearly implied in Thorp's description. Retzer (1949) also emphasizes the extreme importance of age in the weathering of minerals and the development of "distinct, dense" subsoils often "several feet thick" in the Rocky Mountains of central Colorado.

The age or time of exposure plays a very great role as to the determination of minerals present at any one time in tropical soils. Mohr (1944, p. 142) has proposed five weathering stages in the development of tropical soils. His classification is as follows: (a) the beginning stage, the point of departure, the unweathered parent material; (b) the juvenile stage, where the weathering has begun, but there is still much material unweathered; (c) the virile stage, where the weathering has

progressed to a point where unweathered material is not dominant; (d) senile stage, where the weathering of unweathered material is nearing completion; and (e) the end stage, where the development has been completed. The soil is weathered out. This proposed hypothesis considers that the mineral weathering which is responsible for soil formation is in a dynamic equilibrium with its environmental factors. A static equilibrium will, according to this hypothesis, exist only when the end stage is reached. The intensity of the other soil-forming factors will influence (Mohr, 1944) the rate at which the original primary mineral weathers to a series of other minerals which will ultimately reach the end stage.

IV. Frequency Distribution of Minerals in Soils in Relation to Chemical Weathering

Chemical weathering and to some extent deuteric and hydrothermal alteration of minerals, as pointed out in Section I, 2c, are directly or indirectly responsible for the colloidal minerals which occur in soils. Geochemical weathering has been shown in Section III to be controlled by factors which to a large extent can also be identified as operative in the "five factors" controlling soil formation, namely, climate, vegetation, relief, parent material, and time. It is clear that much of the chemical weathering of mineral materials now existing in soils took place during geologic time, including cycles of erosion and sedimentation. Likewise, much chemical weathering took place in the material while it stood in the geologic column prior to its exposure to soil-forming agencies. Some chemical weathering of minerals has taken place in the soil itself during the processes of its formation.

Consideration is now to be given to the stage of chemical weathering of minerals found in soils of various kinds. The extent to which chemical weathering can be correlated with soil formation, as distinguished from geologic occurrence outlined in the previous paragraph, will be considered briefly in so far as it has been determined for each soil analysis.

1. *Soils in the Early Stages of Chemical Weathering*

Early stages of chemical weathering of soil minerals are defined for convenience of discussion to include mineral weathering stages 1–5 of the weathering sequence of Jackson *et al.* (1948, 1952), as outlined in Section II, 1c. Soil materials are considered which contain saline deposits including gypsum (stage 1), calcareous sediments (stage 2), olivine–hornblende minerals (stage 3), biotite, glauconite, and ferromagnesian chlorite (stage 4), and feldspars in the fine fractions (stage 5).

a. Early Weathering Stages Occur in Soils of Both Cool and Warm

Regions. Although the early stages of chemical weathering occur most extensively in regions of cool climates, early stages of weathering occur also in warm tropical and equatorial regions. The difference lies largely in the time during which the early stage minerals can persist under conditions of widely different intensity of weathering. Feldspars can and do occur in the finer fractions of some soils in the tropics but remain only for a relatively short time on exposure to high rainfall and high temperature. Thus Tamura (1951) found feldspar in the silt and coarse clay of the surface horizon of the Naiwa soil family, which is classified as a Ferruginous Humic Latosol. This finding suggests a relatively recent deposition of minerals over the surface of the site of the profile studied.

The youthful soils in the tropical regions are formed on lava, volcanic ash, or sedimentary rock. The initial soil development depends to a large extent on the amount of annual precipitation and on the susceptibility of the rock to decomposition. In the arid regions, the soils are likely to be of the Red Desert group. These soils show evidence of very little mineral weathering. According to Cline *et al.* (1953), the minerals of the parent rock are dominant in soils formed under such a climate. In general, weathering is so rapid in tropical areas that wherever there is an appreciable amount of rainfall, the parent rock weathers rapidly to minerals of the intermediate or advanced stages of weathering.

b. Saline Stage of Weathering (Stage 1). The occurrence of soluble salts, including gypsum, characterizes the mineralogy of soils in the saline stage of weathering. Polders clay reclaimed from the sea in the Netherlands and saline soils in arid regions best exemplify this stage. The presence of ferrous sulfide and its hydrates in poorly drained "gyttja" soils of north Sweden and Finland has been studied by Wiklander and Hallgren (1949) and Wiklander *et al.* (1950a, 1950b) and earlier by Naumann (1918). The sulfide in the presence of air changes to sulfur, and then slowly to sulfate, whereupon a very acid reaction develops. Surface crusts of sulfates form when the sulfide content has been high. The strong acidity causes the rapid weathering of minerals present. The occurrence of up to 30 per cent of gypsum in certain horizons of a tropical soil derived from shale is reported by Rodrigues and Hardy (1947), and 14 per cent of gypsum was reported in a Brown Desert soil of China (Hseung and Jackson, 1952).

c. Calcareous Stage of Weathering (Stage 2). Content of calcite, dolomite, aragonite, siderite, and other moderately insoluble carbonates characterizes soils of the calcareous weathering stage. The most frequent occurrence is of calcite, $CaCO_3$, in the depositional horizon of pedocals (Marbut, 1935). This horizon marks the average depth of penetration

of soil moisture in soils of the arid regions. The identity of the deposited carbonates in this type of zone as the mineral calcite has been noted in several laboratories (Jackson *et al.,* 1948).

Occurrence of about 10 per cent of calcite in the A horizon of Desert and Chestnut soils of China was reported by Hseung and Jackson (1952). Walter Fitts found up to 75 per cent of calcite in Minatare soil of Nebraska, and G. A. Bourbeau noted calcite and dolomite crystals formed in organic fragments in the A horizon of a Podzol of Wisconsin (reported in Jackson *et al.,* 1948). Jenny (1941) showed the removal of calcium carbonate from soils as a function of time ranging from 250 to 1000 years.

In tropical areas having a very strong and long dry season, a calcareous crust forms in the soil. Vageler (1933) and Charles (1948) describe the formation of the calcium carbonate crusts in tropical soils. The latter refers to it as a "calcareous carapace."

Sherman (1937) and Sherman and Thiel (1939) noted the occurrence of dolomite pedogenically formed in the Ulen and Bearden soils in the Red River Valley of Minnesota. The occurrence of dolomite in this area is associated with a high content of magnesium salts in the soil. Although the exact mechanism of the process has not been established, the evidence indicates that the calcium carbonate is altered to dolomite by magnesium sulfate with concurrent deposition of concretions of gypsum. Sherman *et al.* (1947) found pedogenic dolomite in the soils of the Dark Magnesium Clays of the Hawaiian Islands. These soils receive seepage waters from weathering basalts of higher elevations. These seepage waters are rich in magnesium salts.

d. Ferromagnesian and Feldspar Stages of Weathering (Stages 3, 4, and 5). The occurrence in the fine fractions of easily weathered minerals, including ferromagnesian and feldspathic minerals, characterizes soils in which chemical weathering is in the early stages. Colloidal feldspars have been termed "rock flour" and are chiefly the products of physical weathering, particularly the product of grinding by glaciers. As in the case of calcic minerals in soils of stage 2, the colloidal ferromagnesian and feldspar minerals can only be present as a residue from relatively low intensity and short time of weathering because they have a high weathering capacity factor. They occur commonly in silt and sand (low surface capacity factor).

The colloid (particles less than 0.2μ in diameter) of Abitibi silt loam C horizon of the northern Quebec locality was approximately 50 per cent feldspars (stage 5) of the andesine–albite series (Jackson *et. al.,* 1948). Ten to fifteen per cent of amphibole and ferromagnesian chlorite (stage 4) were present, as shown by their characteristic diffraction lines. Some

quartz and mica (stages 6 and 7) made up the remaining part; the mineral composition thus represented a distribution curve centered at stage 5 (Jackson *et al.*, 1948, Fig. 2). The coarse clay (particles 0.2–2μ) has more chlorite and amphibole but was otherwise similar.

Rideau clay soil, B horizon, from the southern Ontario locality showed abundant (40 per cent) feldspars in the fine colloid as well as in the coarse clay, but had much (30 per cent) quartz (stage 6) and less ferromagnesian minerals (Jackson *et al.*, 1948). Similar analyses were obtained of the fine and coarse clay fractions of St. Rosalie and St. Damase soils (A horizons) of southern Quebec; 20–35 per cent of the fine colloid (particles less than 0.2μ) was andesine–albite series feldspars. It is interesting to compare the weathering in these soils, in which stages 3–5 are disappearing at the age of 5000–10,000 years, to that in soils reported by Jenny (1941), in which stage 2 is disappearing at the age of 250–1000 years. Jeffries *et al.*, (1952) correlated the content of feldspars in soils of Puerto Rico with the productivity rating of these soils.

Contrary to the belief of his time that soil clays were merely ground up feldspars, quartz, and micas, Tamm (1920) concluded that clays of soils were formed in part by chemical weathering. Disintegration of a granite by grinding in cold water and in the presence of carbon dioxide (Tamm, 1924) yielded a product 16 per cent of which he considered to be formed by chemical weathering. From self-grinding of feldspars in water suspension (Tamm, 1930), a size fraction of 0.2–2μ was obtained; ionic release from microcline yielded a pH of 10.7 and from oligoclase, a pH of 11.1. With the latter, treatment of the suspension with acid resulted in an irreversible exchange for bases and liberation of aluminum ions throughout the pH range of 11–3. With the microcline, the exchange reaction with acid was reversible in the range 10.3–6, but was similar to the oligoclase reaction below pH 6. Feldspar particles greater than 2μ in diameter were little attacked. In later experiments Tamm (1934) ground feldspars, micas, and other minerals in benzene suspension to prevent chemical weathering, but a rise in pH and the release of cations still resulted.

2. *Soils of Intermediate Stages of Chemical Weathering*

Intermediate stages of chemical weathering of soil minerals are defined for convenience of discussion to include mineral weathering stages 6–9, inclusively, of the weathering sequence given in Section II, 1c. Soil materials are to be considered here which contain quartz (stage 6), micas (stage 7), interstratified 2:1 layer silicates and vermiculite minerals (stage 8), and montmorin series minerals of the more stable species (stage 9).

a. Intermediate Weathering Stages Occur in Soils of Both Cool and Warm Regions. Although the minerals of intermediate stages of weathering occur most abundantly in soils of the temperate regions, they also occur in cold regions and in warm tropical and equatorial regions. The occurrence of montmorin and kaolin in the cool climate of Norway, Sweden, and Denmark seems to be limited to geological formations the weathering product of which was protected from removal during the Pleistocene period. The occurrence of minerals of intermediate weathering in warm regions is limited to areas of long intense dry seasons. Under these conditions the "tropical black soils" have developed, such as the well-known "regur" soils of India, which are considered in connection with the occurrence of montmorin, below.

b. Quartz Stage of Weathering (Stage 6). Quartz occurs generally in small amounts in fine colloids of soils. It is relatively abundant in the coarse clay fraction (particles 0.2–2μ in diameter) of soils in the glaciated temperate and cold regions. In the warmer regions, the quartz extinction function with size is a good measure of the degree of weathering of the soil material, as has been brought out in connection with the size function, Section III, 1c. It is to be kept in mind that quartz in the coarse silt- and sand-size ranges is one of the most weathering-resistant minerals, and thus the quartz stage 6 is limited to the finer size ranges of particles.

Quartz colloids constituted 15 per cent of the fine colloid (particles less than 0.2μ) of Abitibi silt loam, C horizon, in the northern Quebec locality, and a similar percentage of this fraction of Rideau clay soil of southern Ontario (Jackson *et al.*, 1948). Quartz constituted about 5 per cent of the fine colloid of Miami silt loam of Wisconsin, but made up 15 per cent of the fraction from 0.08 to 0.2μ of this soil. In general about one-third of the coarse clay fraction (particles 0.2–2μ in diameter) of soils in the North Central Region of the United States is made up of quartz. Quartz is much less abundant in the coarse clay fraction of many soils derived from mica-rich material. Quartz constitutes much of the light-colored material in the A_2 horizon of Podzols.

Small quantities of quartz, from 1 to 5 per cent, are generally found in the fractions less than 2μ in Latosols of Hawaii (Tamura, *et al.*, 1953). Quartz made up 65 per cent of the fractions smaller than 5μ in the Yatzei "Podzol" of China (Hseung and Jackson, 1952). This soil is derived from cherty material which is unusually resistant to weathering. It occurs in a region occupied normally by Latosols, and accordingly had appreciable kaolin, hematite, and gibbsite.

c. Mica-Illite Stage of Weathering (Stage 7). The mica stage of chemical weathering refers to the occurrence of a maximum in the dis-

tribution curve at stage 7 (mica) when colloidal mineral percentage is plotted against weathering stages of the weathering sequence presented in Section II, 1c. The mica stage includes the mica having the typical 10-A. diffraction spacing. Minerals of this stage have been termed illite, sericite-like, glimmerton, muscovite-like (Correns, 1936; Grim *et al.,* 1937; Maegdefrau and Hofmann, 1937), and are included as one portion of the so-called hydrous micas. In the interest of clarity, the interstratified and other 2:1 layer silicates (of stage 8) which do not have an observable 10-A. diffraction spacing and of which the interlayer spacings are expansible to a lower degree than montmorin on solvation but which still contain some nonexchangeable potassium, are excluded here and presented as separate stage 8 (Section IV, 2d) below. Consistent with this distinction, in introducing the term illite, Grim *et al.* (1937) state that the name was proposed "as a general term for the clay mineral constituent of argillaceous sediments belonging to the mica group . . . it is not proposed as a specific name." It was distinguished from hydromica by the higher than usual water content of the latter.

Mica weathering is of first importance in connection with chemical weathering of soil minerals because (a) micas occur in many kinds of rocks, including those of igneous, metamorphic, and sedimentary origin, (b) micas constitute an important part of soil minerals in the colloid as well as silt and sand fractions, and (c) micas are an important weathering source of available soil potassium.

Grim (1942, p. 259) states: "It is likely that illite is formed infrequently in soils, whereas kaolinite and montmorillonite are commonly formed by soil-forming processes. Illite is present in many soils, but is usually as a remnant of the composition of the parent rock." This observation on the residue mechanism for the occurrence of micas in soils is borne out rather consistently by studies in many places. Feldspar on weathering was found to yield dioctohedral micas (Stephen, 1952a, 1952b) in part through the occurrence of mica as hydrothermal inclusions in the feldspar, but also through subsequent further crystallization of mica.

According to Ross and Hendricks (1945) the occurrence of micas in the western part of the Great Plains of the United States and also in the glacial accumulations in the eastern section of the Plains is attributable to the mica content of crystalline rock and reworked shales occurring in these areas. The clay fractions of these soils therefore characteristically contain more mica and less of the montmorin series than do those of the Central Plains.

Alexander *et al.* (1939) reported dominance of hydrous mica in the clay fraction of the Miami soil of Indiana. Micas in smaller amounts

were reported in soils throughout the eastern United States. They found considerable mica in clay fraction of Carrington soil of Indiana and Barnes soil of South Dakota, along with some montmorin. Several samples of Barnes, Moody, and similar soils of eastern South Dakota have been examined by the senior author, and montmorin has dominated the colloid fraction, less than 0.2μ, whereas micas were important in the coarse clay, 0.2–2μ in diameter. Kelley and Dore (1938) reported mica to be the chief colloidal constituent of the Hanford and San Joaquin soils of California. Barshad (1946) likewise found mica to be the chief colloidal constituent of Cayucos, Gleason, and Sheridan Prairie soils of California.

Drosdoff and Miles (1938) noted a marked dispersion of mica-like fragments by the action of hydrogen peroxide on a Desert soil from California. Alexander *et al.* (1939) noted 70 per cent of the 2 : 1 layer silicates in the colloid of this soil but did not differentiate the extent of interlayer expansion. The colloid of less than 0.2μ of this soil showed strong and distinct lines for montmorin (18 A.) and mica in later studies (Jackson and Hellman, 1942), whereas the coarse clay showed extremely strong diffraction at 10 A., indicative of mica. Evidently the mica had weathered in part to montmorin. Illite predominated in the Mohave soil of Arizona, but some montmorin occurred in it as well (Jackson and Hellman, 1942; Buehrer *et al.*, 1949). Bidwell and Page (1951) noted a prevalence of micaceous minerals in soils of the Miami catena of Ohio regardless of the drainage profile, ranging from the Bethel to the Brookston series. Small amounts of montmorin in association with large amounts of mica were indicated by the thermal and X-ray diffraction data on those fractions less than 0.5μ in diameter. Micas were reported in the percentage range of 20–40 per cent in the clay fraction of Grenada, Sarpy, Atwood, and Norfolk soils (Coleman and Jackson, 1946); in combination with montmorin in several Ontario soils (Webber and Shivas, 1953); and in eleven Pedocal soils of China (Hseung and Jackson, 1952).

Illite was found to be abundant in the black soils of central France (Collier, 1948). Illite was reported in Scotland (Mackenzie *et al.*, 1949) in association with small amounts of montmorin, and the weathering sequence feldspar–illite–montmorillonite was suggested. The presence of a mica, identified as muscovite, was shown in Netherland clays (Baren, 1934), and the occurrence of mica with important amounts of montmorin and a little kaolin was further shown (Favejee, 1939; Edelman *et al.*, 1939). Quartz was also an abundant constituent in the clay fraction. Favejee (1949) found glauconite in the 0.5-μ fraction of a soil in the south Netherlands, and suggested this size for the upper limit of the clay fraction. He further stated that the soil clay mica generally was not

muscovite. Stremme (1951) reported an iron–illite in a brown forest soil in Germany. Illite appeared to be the principal silicate mineral in a blue marl of Switzerland (Sigg and Steiger, 1950). The most extensive soil colloidal mineral in Switzerland soils is illite (Iberg, 1953), but numerous occurrences of montmorillonite–beidellite were observed. Nontronite was observed in weathered granite, and kaolin in old soils.

The prevailing clay-size minerals in the sticky clays in Norway are hydrous mica, according to work reported by Brudal (1940) carried out with the cooperation of H. G. Byers. More recent work by Rosenqvist (1942, 1949) shows hydrous mica (illite) to make up over half of the fraction less than 2μ in diameter in the sticky clays of Norway. Illite was reported to be the most common mineral in soils of Sweden (Wiklander, 1950a, 1950b) in soils formed predominantly from varved glacial and postglacial material. Quartz was found to be common and feldspars detectable by X-ray diffraction. Some of the illites showed a strong benzidine reaction, but others did not. As an exception to the above trend, montmorin was found to be abundant in the till clays of Scandia.

Mica predominated in a dry sierran soil of the highlands of Ecuador (Miller and Coleman, 1952). Evidence of mica was adduced in the Humic Latosol of Hawaii on the basis of potassium content and allocation of hydroxyl and elemental analysis (Tamura *et al.*, 1953).

d. Interstratified 2:1 Layer Silicate and Vermiculite Stage of Weathering (Stage 8). Interstratified 2:1 layer silicate refers to the mixing of layers of various layer silicates within a given single crystal. Layer silicates which exhibit such mixing include the micas, vermiculites, montmorins, chlorites, pyrophyllites, and talcs. The chief analytical manifestations of such interstratification are (a) a disruption of the basal diffraction intensity spacings and (b) production of intermediate properties as represented by elemental analysis and specific surface. Included with weathering stage 8 also is vermiculite, which has more highly charged layers than montmorin and consequently has less freedom of interlayer expansion. The properties of the layer silicates of this stage of weathering (stage 8) are intermediate between those of micas (stage 7) and montmorin (stage 9). The stage 8 minerals have been termed "partially expanding" (Jackson and Hellman, 1942) and "mica-intermediates" (Jackson *et al.*, 1948), though they properly should be called mica-montmorin intermediates, since the entire range of properties intermediate to micas and montmorins are found in different specimens. Because the vast and important differences in properties of these "partially expanding" 2:1 layer silicates from those of the micas (including the nonswelling illites having a 10-A. diffraction spacing), they clearly should be placed in different weathering stages. The weathering mean (Sec-

tion II, 2c) thus reflects the weathering change associated with a shift from the true micas to the partially expanded materials by the shift of the stage number from 7 to 8.

Gruner (1934, p. 561) stated that the potassium-bearing vermiculites are made of interstratified layers of mica and vermiculite. Clark *et al.* (1937) noted the absence of a basal diffraction spacing in soil clays which did have the typical 4.45 A. line of layer silicates. They stated that soil clay layer silicates might have to be taken as "entity" rather than being characterized further as having a definite structure. Hendricks and Jefferson (1938) stated that mixtures of vermiculite with mica, chlorite, pyrophyllite, and talc layers would be expected.

Alexander *et al.* (1939) suggested "mixed layers" (interstratification) of 2:1 layer silicate components on the basis of their X-ray diffraction analysis of several soil clays. Jackson and Hellman (1942) noted a shift in the basal spacing of certain types of hydrous micas that exhibited swelling properties and reported a 12-A. diffraction spacing from these swelling types of hydrous micas. Hendricks and Teller (1942) provided mathematical interpretation of the diffraction phenomena to be expected from interstratified materials. These functions were presented graphically by Brown and MacEwan (1950). Nagelschmidt (1944) also obtained intermediate basal spacings from glauconite and from some illites. He concluded that the spacing indicated interstratification.

Ross and Hendricks (1945) pointed out the growing recognition of the importance of interstratified 2:1 layer silicates, and the fact that intermixtures of such minerals with the montmorins must be considered. Montmorin clays "may contain mixed layers of mica, chlorite, talc, or brucite and possibly other minerals of similar character." They also state that "as beidellite is approached there is a decided tendency toward formation of mixed layer type minerals containing potassium." However, Gieseking (1949) stated that chlorite was the only interstratified mineral conclusively shown to be present in soils.

A progressive weathering of biotite in soil, through mixtures of mica and vermiculites, to vermiculite was reported by Walker (1949). He states that "... leaching of potassium from interlayer positions together with replacement of iron in the interior of the silicate layers by magnesium and other ions from percolating waters reduce the attractive interlayer forces and permit the entry of double layers of water molecules. This latter phenomenon spreads through the crystal layer by layer, by giving first a mixed-layer structure in which increasing numbers of layers become the vermiculite type." Increasing amounts of montmorin in association with mica weathering were found with decreasing

particle size in soil materials weathered from granite (MacKenzie *et al.*, 1949). Walker (1950) reported both trioctahedral vermiculite and montmorin formed from biotite. The diffraction maxima of weak, medium, and sometimes strong intensity at a spacing of 14.3 A. was found (Pearson and Ensminger, 1949) for a number of soils including Norfolk, Orangeburg, Ruston, Greenville, Davidson, Decatur, and Hartsells. This spacing did not increase to 18 A. with treatment with glycerol, indicating the presence of a vermiculite-like or chlorite-like mineral. Pearson and Ensminger (1949) state: "In none of the clays included in the present study is a characteristic hydrous mica line observed." Complex interstratification of vermiculite, chlorite, mica, and montmorin has recently been found in these Davidson and Hartsells (Heuvel and Jackson, unpublished). Coleman *et al.* (1950) reported vermiculite and clay intermediates in Norfolk, Bladen, and Alamance soils of North Carolina (strong 18 A. diffraction of montmorin also occurred with the Bladen soil). A wide distribution of vermiculite and interstratified materials was reported in soils of China (Hseung and Jackson, 1952). Occurrence of vermiculite in an equatorial soil of South America was reported by Barshad and Rojas-Cruz (1950).

Dyal *et al.* (1951) reported on mineral content on a number of Red-Podzolic soils from the southeastern United States. The results were expressed as percentage of "inner-surface" minerals, kaolin, quartz, and gibbsite. The first category was determined as the percentage of inner surface in ratio to that of "volclay" (Wyoming bentonite). The inner surface minerals comprised from about 10 to 60 per cent of the clay fraction less than 2μ in diameter. Kaolin comprised on the order of 15–30 per cent but as high as 50–60 per cent in a few samples. Quartz and gibbsite were minor constituents. The classification given for inner surface minerals includes minerals of the montmorin, vermiculite, and expanding layers interstratified with mica minerals. The results concur well with those reported by Coleman and Jackson (1946), if the weighted average is taken by the two size fractions reported by the latter authors in comparison with the results of the combined total clay (less than 2μ) by the former.

Bradley (1950a) concluded that mica layers occurred naturally as "discrete minerals, as random layered intergrowths of mixed species, and as regular intergrowths of two complementary species." Alternations of pyrophyllite and vermiculite interspaces were reported in rectorite, and thus the mineral contained scarcely any potassium, yet consisted of 10- and 14-A. spacings interstratified (Bradley, 1950b).

Barshad' (1948, 1950, 1951) showed that a slow exchange of magnesium for the potassium of biotite results in the production of a 14-A.

spacing, and that the reaction is reversible by slow exchange with potassium. Depotassication of biotite through weathering would thus be expected to produce chlorite-like and vermiculite-like layer silicates. The completion of removal of potassium along a given plane at a rate orders of magnitudes faster than the rate of initiation of weathering along such a plane was proposed (Jackson *et al.*, 1952) as the reason for the development of interstratification in the 2:1 layer silicates. This effect was termed the preferential weathering plane principle. It was further proposed that alternate planes of micas are more readily weathered, and thus alternation of opened and closed interlayers was the result. Data on clay materials were presented graphically to illustrate both 10–18–10–18 and 10–14–10–14 sequences. Rolfe and Jeffries (1952) proposed the use of the reversibility of the Barshad depotassication reaction with attendant reversibility of the shift from 10- to 14-A. spacings as an index of weathering and that it was applicable as a depth function.

Stephen (1952a) states that the process of vermiculitization of biotite can occur either through mixed-layer biotite-vermiculite intermediate stages (Kerr, 1930; Wager, 1944; Walker, 1949) or through mixed-layer biotite-chlorite and chlorite-vermiculite stages. Stephen and MacEwan (1951) noted expansion of a chlorite in the range of 14–18 A. in the presence of glycerol. This observation suggests a continuity of interstratification between chlorite, vermiculite, and montmorin.

Marel (1950a) has provided detailed X-ray diffraction data for the various layer silicates that some have interlayer spacings greater than those of micas. He includes spacings for vermiculite, muscovite, illite, and hydrated biotite. He distinguished the latter from hydrobiotite consisting of vermiculite and biotite layers (Gruner, 1934). Marel (personal communication) further calls attention to so-called metabentonites (or mica intermediate or bravaisite, described by Mallard in 1878) in some soils of France and in a clay bed in a coal mine at Noyant d'Allier. Some layer silicates with spacings of 14–15-A. were found not to contract to 10-A. when treated with potassium, and Marel cautions against an identification of the 14-A. spacing with vermiculite in the absence of this potassium-contraction reaction.

Warder and Dion (1952) noted that potassium could be fixed to the extent of twice the cation exchange capacity of the 2:1 layer silicates of soil colloids from Saskatchewan. This indicated the presence of either "(a) a mixture of illite and montmorillonite or (b) a mineral intermediate in properties between illite and montmorillonite" (vermiculite?). They calculated that the colloids approached the composition of beidellite, but that the potassium content and composition indicated the

"strong probability" of the presence of mixed layer minerals containing potassium.

Marel and Bruijn (to be published), noted a layer silicate of 15.6-A. diffraction spacing in abundance in vast areas of alluvial clays in the Netherlands. They designate this by a new mineral name, "ammersooite," but the spacing of 15.6-A. suggests interstratified 2 : 1 layer silicates.

The decrease in intensity and broadening of angle of basal diffraction of weathered micas occurring in soil colloids could arise in part from increasing content of amorphous material as a diluent (Pennington and Jackson, 1948; Gieseking, 1949), but the persistence of the (110) diffraction line out of proportion to the residual basal spacing, observed in many laboratories (Clark *et al.*, 1937; Jackson and Hellman, 1942), suggests randomness in the (OOL) sequence, with preservation of the layer structure responsible for the (110) diffraction line. The principal change accompanying mica weathering, a broadening of the angle of basal diffraction as well as the decrease in basal diffraction intensity, is believed (Jackson *et al.*, 1952) to arise from the decreasing number of layers having a 10-A. spacing in each zone not interrupted by vermiculite or montmorin interspaces, toward the minimum number for X-crystallinity.

On the basis of internal surface measurements together with water, hydroxyl, and diffraction intensity data, the existence of interstratification in micaceous materials deficient in K was proposed (Jackson *et al.*, 1952) for a variety of materials including glauconite, illite, and a number of so-called illitic soil clays. This conclusion may be summarized as follows:

Mica + (expanded spacings) = (illite, sericite, glauconite, etc.) According to this concept, to speak of mixed structures of illite plus expanded spacings becomes redundant, since illite is characteristically interstratified. Only when interstratification caused noticeable interruption of the 10-A. sequences and associated diffraction intensity had it been generally recognized or emphasized in much of the literature.

Failure to recognize the interstratified nature of illite has led to considerable confusion in the interpretation of soil layer silicates. The occurrence of some potassium in the material in the absence of potassium feldspar, of course, proves the presence of some micaceous material. Since the type illites vary greatly in the quantity of mica present (that is, in their K content), materials which are considerably interstratified with vermiculite and montmorin sometimes have been loosely designated as illite. It now appears certain that analyses by means of diffraction, differential thermal, water and hydroxyl, and elemental analysis techniques will permit a quantitative assignment of the components of

interstratified 2 : 1 layer silicates to the categories mica, chlorite, vermiculite, and montmorin, with the result that considerable confusion will be avoided in their analysis.

Thus Bray (1937a) reported 75 per cent mica and 15–20 per cent montmorillonite in his illite sample DS 43. Also, the illite from Fithian, Illinois (Pennsylvanian underclay from R. E. Grim, Illinois State Geological Survey and locality as listed in American Petroleum Research Project 49 in 1950), used by Talvenheimo and White (1952), showed an 11.3-A. spacing when exchange-saturated with divalent cations, particularly with Mg. These authors conclude that even this specimen illite consists in part of interstratified montmorin material. Likewise, Martin and Russell (1952) noted surface equivalent of 30 per cent montmorin in an illitic soil clay of New York. Lack of a basal spacing in colloidal minerals of Gainsville soil which had the appearance of mica in the electron microscope was reported by Dyal (1953). He stated in his oral presentation that the material showed electron diffraction from the prismatic (110) spacings.

The general conclusion is reached that 2 : 1 layer silicate colloids have all degrees of interstratification, from traces of expanded spacings probable in muscovite and biotite specimens to traces of unexpanded spacings in montmorin specimens, with all gradations between (Jackson, *et al.* 1952). Variation of layer charge density from 250 meq. per 100 g. of true micas to the negligible charge of pyrophyllite layers seem probable, with all degrees of associated expansibility from none (mica, pyrophyllite) to restricted (vermiculite, chlorite) to free expansion (montmorin). A frequency distribution of the layer charge density was proposed by Jackson *et al.* (1952), and as this distribution varies from a narrow one to a broad one, the analysis varies from nearly discrete species (mica, vermiculite, chlorite, or montmorillonite) to a less readily characterized interstratified layer silicate. Even in the samples of narrow distribution of layer charge density, some degree of interstratification is to be expected.

e. Montmorillonite Stage of Weathering (Stage 9). The montmorillonite stage of chemical weathering of minerals refers to the occurrence of a maximum in the distribution curve at stage 9 when mineral percentage is plotted against mineral weathering stages of the weathering sequence presented in Section II, 1c. The montmorillonite stage also includes beidellite and saponite but does not include nontronite, which is in stage 4. Thus the montmorillonite stage cannot be considered commensurate with the montmorin series as a whole. Nontronite is believed to be uncommon in soil colloids because of its lower weathering stability. The criteria employed for the occurrence of montmorin as discussed

herein include diffraction spacings of approximately 18 A. and the occurrence of the characteristic differential thermal, surface, and titration curve properties.

The montmorillonite stage seems to occur in predominating amounts in the colloidal, and sometimes in the entire clay, fractions of soils in the following situations:

1. Clays formed in fresh water deposits of volcanic ash (the bentonites, reviewed extensively by Ross and Hendricks, 1945, and therefore not elaborated herein).
2. Clays formed in or from marl, dolomitic limestones, and basic rocks where weathering has progressed to intermediate stages.
3. Fine layer silicate colloids formed in upland deposits and soils by weathering of micas in cool humid climates (for example, in the Mississippi Basin of United States).
4. Clays formed in hydromorphic deposits and soils in flat uplands and valleys (for example, in Planosol B horizons and Dark Magnesium Clays).

Representative of montmorin formed from volcanic ash (aside from the extensive deposits considered by Ross and Hendricks, 1945) are several deposits in Japan. A montmorin rich in iron was formed in a thick tuff in Tochigi Prefecture (Ota, 1949; Ota and Sudo, 1949; Sudo, 1950c). The material contains some volcanic glass fragments which exhibit only a slight alteration to montmorin on their exposed surfaces. The presence of liquid inclusions and quartz phenocrysts in the fragments suggest that they are of acidic nature. Sudo suggests that the ash fragments contained a good deal of volcanic vapor which was trapped within the fragments as they become cemented under sea water. The volcanic vapors then rapidly weathered the fragments. Detailed mineralogical studies on this material (Sudo and Ota, 1952) reveal that the variously colored clays altered from the rock fragments are montmorin, whereas the green clays in deeper zones are of a variety of montmorin rich in iron.

Young pumice tuff or tuffaceous sediments have frequently altered to montmorin (bentonites and acid clays in northeastern Japan) (Sudo, private communication). Certain of the bentonites occur under poor leaching conditions, but others occur as lenticular or irregular bodies situated near hot springs. Acid montmorin which occurs in association with bentonite (Kobayashi, 1949; Otsubo, 1950; and Sudo, 1950a, 1950b) has a stronger adsorptive power, a higher silica: alumina ratio, less Mg and Fe, and a smaller degree of swelling than the bentonite. The bentonite, however, when treated with weak acid, produced an artificial clay with a strong adsorptive power, similar to that of the natural acid clay.

Sudo (private communication) considers that the acid clay is formed by leaching of very acid tuff or by leaching of the bentonite with acidic surface or hotspring water.

Representative of montmorin occurrence in soil material formed from marls, dolomites, and basic rocks are the following examples. Houston clay derived from marl was reported to contain montmorin in Texas by Hendricks and Fry (1930), in Mississippi by Coleman and Jackson (1946), and in Alabama by Pearson and Ensminger (1949). The colloid of Miami silt loam of Wisconsin, developed on dolomitic till and well-drained, is dominantly montmorin, as shown by the 18-A. diffraction criterion as well as by surface and cation exchange properties (Jackson and Hellman, 1942; White and Jackson, 1947). Kelley and Dore (1938) reported an association of montmorin with soils developed on basic igneous rocks. Montmorin occurred in the Porterville, Maxwell, and Yolo soils. Hosking (1940) reported montmorin formed in Australia from basalt under low enough rainfall that leaching was retarded and also from basalt when the drainage was so impeded as to cause water logging. Under active leaching kaolinite was formed.

Representative of montmorin series minerals in the fine colloids (particles less than 0.08μ) weathered from micas are the following examples. Bray (1937b) reported beidellite in the Hartsburg–Cisne sequence of soils in Illinois. Engelhardt (1937) reported nontronite (with mica) in the colloidal fractions of a soil from the Mecklenburg locality. Alexander *et al.* (1939) reported montmorin in the Barnes soil of South Dakota. The montmorin series made up 50–65 per cent in the less than 0.3-μ fraction of Clarion, Grundy, Tama, and Weller soils of Iowa (Russell and Haddock, 1941). Kaolin made up 5–20 per cent and illite 15–35 per cent of these soils. Montmorin constituted 85 per cent of the Webster finer clay fraction. These results are based on differential thermal analysis and on the nonexchangeable potassium content in the case of illite—methods which in general resolve the interstratified 2 : 1 layer silicates into their component mica and expanded spacings. These analyses have been confirmed by the 18-A. diffraction line in the senior author's laboratory. The analyses illustrate a distribution curve centered at stage 9 of the weathering sequence (Section II, 1c), with lesser amounts of stages 7 and 8 and 10. Abundance of montmorin was further shown in the colloids of Webster, Marshall, Tama, Edina, and Clinton soils of Iowa (Peterson, 1946a) by means of X-ray and differential thermal methods. Shelby soil contained montmorin with considerable kaolin. Barshad (1946) noted montmorin in the Colma Prairie soil of California.

Montmorin is the dominant mineral colloid in the Carrington, Marathon, and Fayette (Clinton) soils of Wisconsin and in the Moody soil

of South Dakota (Jackson and Hellman, 1942). Humbert and Marshall (1943) report beidellite in two soils of Missouri, one developed from granite and the other from diabase. This occurrence suggests the production of a specific type of weathering product in a given environment rather than a control by the parent material of the mineral formed.

Larson *et al.* (1947) noted the presence of abundant montmorin in the fine fraction of Pawnee and Scott soils of Nebraska. Similarly, Larson *et al.* (1948) noted abundance of montmorin in the fine clay fraction of the Holdrege, Keith, and Dawes soils of south central Nebraska. The coarse clays of these soils contained abundant mica minerals with some montmorin. The authors concluded that considerable quantity of the fine clay was formed by weathering in place, but that the qualitative nature of the minerals had not been materially changed during soil development. Buehrer *et al.* (1949) found from 30 to 50 per cent montmorin in the colloids of a number of Arizona soils. The illite contents reported ranged from 50 to 70 per cent of the colloids, on the basis of 6 per cent K_2O in illite. The presence of more than 50 per cent montmorin was considered indicative of possible poor agricultural characteristics of the soils owing to ease of dispersion, tendency to swell, and difficulty of reclamation. The montmorin colloids showed endothermic reactions at 550–600° C., together with strong endothermic peaks at approximately 175° C. The endothermic peaks of montmorin at 550–600° C. appeared at a somewhat lower temperature than that often obtained in standard bentonite, such as an Otay specimen which gave an endothermic peak at 925° C. in this work. Likewise, Warder and Dion (1952) reported an endothermic peak in the region of 525° C. by differential thermal analysis, which was lower than the 650° C. peak typical for many montmorinic bentonites. The shift to lower temperature is typical of soil montmorins. The occurrence of the montmorin series was established by means of powder diffraction patterns. In this connection, Martin and Russell (1952) noted, on the basis of surface data, "up to 30 per cent" of montmorin in a New York soil colloid, but doubted this interpretation because of the occurrence of the endothermic peak at 550° C. instead of at the higher temperature typical of bentonites. Mackenzie *et al.* (1949) attributed a broad 550–600° C. peak to montmorin and a 713° C. peak to illite—an interpretation just the reverse of the usual standards for these two mineral series. It is concluded by the present writers from evidence presented by many workers that isomorphous substitution can shift the endothermic peak of each series throughout the range of both, octahedral iron lowering it and magnesium raising it from an average value with aluminum.

Montmorin was found in considerable amounts in the colloids of Pil-

chuck, Sultan, Puyallup, and Puget soils in the state of Washington (McHenry, 1952). These soils were developed on recent glacial alluvium. The coarse fractions consisted largely of quartz and mica. Occurrence of montmorinic clays in some localities of Denmark is reported by Unmack (1949) in three geologic formations. In one of the samples, anatase was also present in the finer fractions. Montmorin was reported in the Karasu Gray Desert and the Chungking noncalcic purple brown soils of China (Hseung and Jackson, 1952). Miller and Coleman (1952) reported abundant montmorin in a dark gray calcic soil of tropical Ecuador and also in a moist sierran soil of the highlands of Ecuador. Rather widespread occurrence of mixtures of montmorin and mica in the fraction less than 1μ was found by Warder and Dion (1952) in soils of Saskatchewan representative of Gray Wooded, Chernozems, Chestnut, Solod, and Solonetz-like soils. It was concluded (Warder and Dion, 1952) that the clay mineral composition is similar to that in the parent materials and is not affected by the amount of weathering during soil formation. The minerals were considered to have been inherited from shales from which the parent material was formed. Nontronite was reported in a brown earth of Switzerland (Geering, 1936); however, the nontronite-like flakes did not show X-ray conformity to nontronite in a later study (Harkort, 1939). The occurrence of a sericite–montmorin complex was suggested. Occurrence of montmorin in some Swiss soils was confirmed by Iberg (1953).

Occurrence of montmorin in the range of 25–65 per cent was reported in the Susquehanna and Oktibbeha soils of Mississippi by Coleman and Jackson (1946). Similar occurrence in these soils and the Eutaw and Houston soils of Alabama was reported by Pearson and Ensminger (1949). Through a glycerol solution technique, the existence of an 18-A. diffraction line in the colloids from Mississippi soils has been confirmed in the senior author's laboratory. Montmorin also was reported in Orangeburg, Sarpy, and Atwood soils of Mississippi and in Susquehanna clayey B horizon and Lufkin A horizon of Alabama (Coleman and Jackson, 1946).

Montmorin as well as kaolin was found in abundance in the Scandia till clays (possibly of preglacial origin) of Sweden (Wiklander, 1950a, 1950b). Wiklander (unpublished) has confirmed the montmorin occurrence in Scandia, and also in an iron-gneiss weathered in the pre-Quaternary period. The weathered rock was ground, and the fraction less than 2μ separated and found to consist mainly of montmorillonite, with exchange capacity, swelling, hygroscopicity, and floc volume exceeding that of Wyoming bentonite. Norin (1941) indicated the presence of montmorin in soils of Sweden formed on Quaternary material. Montmorin

was found in Norway in a weathered green schist (Isachen and Rosenqvist, 1949), and beidellite was reported in a weathered quartz monzonite (Barth, 1939). Montmorin was noted as an important component of Netherlands soils along with much mica and a little kaolin (Favejee, 1939; Edelman *et al.,* 1939). Alexanian (1951) observed the formation of montmorin and some kaolin in a microgranite after exposure to climatic forces for a period of ten to twelve months.

Ross and Hendricks (1945) refer to Lamar *et al.* (1938) on the occurrence of montmorin in gumbotil, a weathering product of glacial material. It is reported common on tills older than the Wisconsin deposits. The latter authors are quoted as follows: "The conversion of till to gumbotil in nature involves oxidation, leaching of carbonates, and chemical decomposition of the silicate materials . . . The original till contained large amounts of clay minerals of the illite group, and in general the process of weathering has tended to remove alkalies, particularly potassium, and to alter the illite minerals to those of the montmorillonite group."

Montmorin rather characteristically occurs in hydromorphic deposits and soils in flat uplands and valleys, both in the temperate and in the tropical regions. Sedletzky (1939) reported montmorin in saline soils of Russia. Hosking (1940) has shown that soils developed on a basalt with an impeded drainage develop minerals of the montmorin series. The dominant minerals found in the clay fraction of the "tropical black soils" are minerals of the montmorin series. Nagelschmidt *et al.* (1940) studied the minerals of a tropical black soil of pH 8 formed on crystalline granite or gneiss and found the dominant mineral to be a montmorin. Raychaudhuri *et al.* (1943) also found that beidellite was the dominant mineral in a tropical black soil in India. The occurrence of similar soils has been described by Merwe (1950) in South Africa (who states that they are similar to the "regurs" of India and the black earths of Australia), Hamilton and Sessler (1945) in the Netherlands West Indies, Fuggles-Couchman (1946) in Tanganijika Territory, Costa (1947) in Angola, Edelman (1946) in Java, Parbery (1947) in Australia, Robinson (1950) in Barbados, Lozet (1950) in Ruzizi Valley, Shiva Rau and Kasinathan (1951) in the Madras, and Cline *et al.* (1953) in Hawaii.

The soils of the "red and black complex" are common soils of the tropical regions. These soils are found in close association under identical climatic conditions but different leaching conditions. Because of their widespread occurrence, these soils have been studied extensively. The black soils are the tropical black soils. Villar (1944, 1950) described the soils of this complex as it occurs in Morocco and found that the black

soil (tirs) resembled the tropical black soils and that the red soil showed evidence of laterization. Thus the soils of the "red and black complex" are probably a transition zone in soil weathering. Ray and Das (1950) found that the black soils of the complex were rich in montmorin and illite, whereas the red soils contained halloysite. Similar findings have been reported by Nagelschmidt *et al.* (1940), Raychaudhuri *et al.* (1943), Hamilton and Sessler (1945), and Merwe and Heystek (1952). Unpublished data from the Hawaii Agricultural Experiment Station indicate that the soils of the "red and black complex" are transitional, in that there is a gradual change from montmorin to kaolin minerals as one examines the soils in detail from a black area to the red area. Likewise, in soils which have a red surface and a black subsoil the same transition occurs. Cole (1940-1941) found kaolin and iron oxides in a surface soil over montmorin in the subsoil.

The evidence presented by Edelman and Schuffeler (1948) indicates that montmorin is found where weathering occurs under a neutral or alkaline reaction, but that kaolin occurs with an acid reaction and more advanced weathering conditions. These conditions are in accord with those of Ross (1943) for kaolin formation. However, numerous occurrences of substantial amounts of both kaolin and montmorin together in the same sample show that both can form by weathering in a given environment or that kaolin develops at the expense of montmorin as weathering progresses.

Weathering of montmorin to kaolin was suggested by Kelley *et al.* (1939a) to occur by the splitting off of silica from the 2:1 layer in the Susquehanna soil colloid. Weathering of a glauconitic greensand first to montmorin then to kaolin was noted in western Australia (Cole, 1940–1941), and a similar mechanism of transformation was suggested. Desilication of one side of a 2:1 layer silicate to form a 1:1 layer silicate was suggested by Jackson *et al.* (1948), but it was also pointed out that formation of kaolin by direct solution of other minerals and reprecipitation of the kaolin crystals is indicated by the large coarse crystals in which kaolin is often found. The desilication mechanism may serve as a starting point of weathering of 2:1 layer silicates to 1:1 layer silicates, followed by the solution and precipitation mechanism.

3. *Soils of Advanced Stages of Chemical Weathering*

Advanced stages of chemical weathering of soil minerals are defined for convenience of discussion to include mineral weathering stages 10–13 of the weathering sequence presented in Section II, 1c. The stage of weathering of a soil is considered to be that of the most abundant colloidal and weathering-product minerals present in it. Soil materials are

considered which contain predominantly kaolin family minerals (stage 10), gibbsite and allophane (stage 11), hematite and goethite (stage 12), and anatase and leucoxene (stage 13). Minerals of the advanced stages of weathering occur mainly in soils of the warm tropical and equatorial regions but also occur in old soils of the temperate regions to a greater extent than is often realized.

a. The Laterite as the End Product of Weathering. Prescott and Pendleton (1952) have reviewed the subject of the laterite in detail, and therefore only the aspects relating to mineral weathering principles will be covered herein. The specialized meanings which have been attached to the term "laterite" have made desirable another term for designation of soils high in minerals of the advanced stages of weathering, and the term widely employed for this purpose by soil scientists is "Latosol." The process of development of Latosols may well be designated *latosolization.*

The laterite was first ascribed by Buchanan (1807) to a material which was quarried in South India. It was a soft ferruginous clay which, when sun-dried, hardened into brick which could be used for building material. The term, "laterite," meaning brick-like, comes from the Latin word "later" meaning brick. In spite of this lithological meaning the term "laterite" has been used to designate a great variety of tropical soils including those having a red color, iron-pan layers, and all kinds of ferruginous and aluminous materials occurring in tropical regions. The use of the word to designate such a wide range of soils has led to much confusion regarding the nature of tropical soils. Much of the confusion can be attributed to scientists working with inadequate analytical tools and often with great ignorance of tropical conditions. Consequently, there are many theories as to what constitutes laterite and also as to what basic weathering processes are involved in its development. Even so, there was general agreement that the laterite was the end product of soil weathering.

Mohr (1944), through the translation by Pendleton, has made known the results of his many years of study of the equatorial soils of the Dutch East Indies (Indonesia). Mohr follows the same conceptions of tropical soils as Pendleton, but he has in his possession a large amount of data on the chemical composition of lavas, waters, and soils which in itself is a major contribution. His hypothesis of the age of development of tropical soils (reviewed in Section III, 4) has been a substantial contribution to soil science. The iron oxide accumulation begins in the soil profile in the fourth or "senile stage." The indurate layer of iron oxides is found near or at the surface of the profile in the fifth or "laterite stage," the end product of weathering, when all or nearly all of the primary minerals

of the original parent material have undergone decomposition. At this point in soil development all easily soluble materials have been leached from the soil and hydrogen saturation is nearly complete.

Although there is a group of soil scientists who favor Buchanan's (1807) definition of a laterite as indurated ferruginous clay, others consider aluminum oxide as the key constituent of a laterite. Holland (1903) described the laterite as a weathered material containing alumina in a hydrous form. Warth and Warth (1903) supported Holland by defining laterite as bauxite in various degrees of purity. Fermor (1911, 1915) insisted that the decomposed, weathered product must have a high content of hydrated aluminum oxides to be called a laterite. Fox (1923) considered that any laterite which contained enough hydrated aluminum oxide to be an aluminum ore should be called a bauxite. Leenheer (1944) believes that laterites can become enriched with sesquioxides by the upward movement of water. He considers a laterite to be rich in aluminum hydroxide. Martin and Doyne (1927) proposed the use of the silica: alumina ratio of the clay fraction as the criterion for a laterite soil. This was based on alumina as the essential constituent of a laterite. A low ratio would signify a high content of free alumina. If the ratio was less than 1.33, the soil would be considered a laterite. In recent years the silica: alumina ratio has slowly lost its early emphasis. In general, the geologist looks upon the laterite as being a highly weathered formation rich in hydrated iron oxides.

Pendleton (1939, 1941, 1942, 1946) is an ardent advocate for restricting the term "laterite" to Buchanan's original definition. His definition (1946) is as follows: laterite is the indurated, slaglike or pisolitic, iron-oxide–rich, illuvial horizon in the soil, of such a physical character that the material can be quarried out and used structurally. The laterite horizon, the layer which is largely ferric oxides and which hardens on exposure, according to Pendleton (1946), is formed within the soil. It is often exposed at the surface by erosion. The nature and morphology of the laterite soil profile is determined by the nature of the parent material (Pendleton, 1942). The laterite usually develops in a peneplain. Under peneplain conditions the water table fluctuations are uniform; the soil of the gentle slopes or slight elevations receives the seepage waters due to lateral movement of gravitational water. This water, according to Pendleton (1946), carries ferrous iron. The ferrous iron is carried upward in the soil by the ascending capillary water and is precipitated as ferric iron by oxidation. Pendleton does not consider this layer the laterite horizon until sufficient iron oxides have been precipitated to produce the indurated layer. Pendleton (1946) does not consider the Nipe clay of Cuba (Bennett and Allison, 1928) to be a laterite.

The ferric iron is precipitated as spherical concretions around the insect holes or openings in soils or around aggregates.

Pendleton (1941, 1942, 1946) states that the laterite is the ultimate product of soil weathering. It can be destroyed by erosion, and a new surface exposed to the renewal of soil-forming processes. Although Pendleton believes that the laterite horizon must be ferruginous, he does not believe it is possible to define a laterite in chemical terms. He insists on the morphological description plus the lithological characteristics: namely, the indurated ferruginous horizon and sufficient hardness to make it suitable as a building material. However, Pendleton does admit there is a lack of data regarding the chemical composition of laterites.

Harrassowitz (1926) described a laterite profile in South India and also one from Madagascar. His general description of a laterite is as follows: an iron oxide and aluminum oxide crust horizon near the surface. This would be underlain by a layer of kaolin enriched with iron oxide, which in turn would be underlain by his "zersatz" layer, also known as the "bleichzone." The "zersatz" consists of rocks which have undergone chemical change but retain their physical shape. This layer may have "siallitic weathering," which produces kaolin, or "allitic" weathering, which produces the mono- and trihydrates of free alumina, bauxite.

According to Campbell (1917), laterization is a process in which certain hydroxides, primarily those of ferric iron, aluminum, and titanium, are deposited near the surface. If the indurated horizon did not contain free aluminum oxide he did not consider it lateritic. Campbell considered the saturation caused by a fluctuating water table to have an important role in the development of the laterite. The prior formation of kaolin in the permanently saturated zone was considered to be a prerequisite to laterization.

Mohr (1944) disagreed with the theory that laterites could form only under a wet and dry climate. He believed that the laterite could form in the humid tropical climate by leaching, followed by exposure by erosion. He did place considerable emphasis on the movement of water within the soil and the oxidation conditions of the soil. Mohr considered any month which received more than 4 inches of rain to be wet. Under tropical conditions rainfall in amounts higher than this would not necessarily cause reducing conditions in the soil.

Vageler (1933) considered that weathering in tropical climate would produce either siallitic residues, such as crystalline kaolin or allophane in gel form, or allitic materials, such as aluminum oxide in either crystalline or gel form, and iron hydroxide in gel form. The amounts of each components would depend on the mineralogical composition of the rock.

The intensity of the decomposition would depend on the amount of water present as a solvent and the length of time it was present as the weathering materials. In other words, siallitic residues would occur where soils were predominantly dry, and allitic materials, in the humid areas. He contended that the primary cause of weathering was uniform, but that the final character of the soil was determined by moisture conditions, by the acid or alkaline reaction of the system, and by the nature of the organic matter.

Vageler's concept of the end product of tropical weathering was the indurated ferruginous laterite crust. This profile would include layers of allitic products over siallitic products. The bleached subsoil was the source of iron oxides for the surface crust. Thus, his conception agrees with Pendleton's or Mohr's ideas.

Greene (1947, 1950) considered that seepage of water down the slopes was the chief means by which iron was accumulated in the surface of the laterite. The conditions for the lateral movement of water within the soil profile are quite prevalent in tropical soils. This explanation has been offered for the accumulation of iron oxide in the laterite crusts of Hawaii by Sherman (1950).

In general the recent work in tropical soils still considers the Laterite to be the end product of weathering. However, there is a tendency towards modifying Buchanan's definition to adopt the proposal of DuPreez (1949) to eliminate the requirement that the indurated layer be of sufficient hardness to be used as a building material. The ferruginous indurated clay layer still is considered to be the end product of weathering. Sherman (1950) agrees with DuPreez in that the pedological definition should be adopted. Use of the term "Latosol" has been widely adopted as the pedologic term to avoid the fixed connotations of "laterite."

Sherman (1949, 1952b) has offered the hypothesis that the moisture environment determines the character of the end product of weathering. Under his hypothesis the general weathering of soil minerals would follow this sequence under a strong, dry period alternating with a wet period: primary minerals → montmorillonite → kaolinite → hydrated iron and titanium oxides → dehydrated iron and titanium oxides (Laterite). Under about an even alternation of dry and wet seasons, it is probable that the primary minerals will weather directly from primary minerals to kaolin. Under continuously moist climate the weathering would favor the stability of the aluminum hydroxides. Thus, according to this hypothesis the end product of weathering can range from iron oxides (iron ore) to aluminum hydroxides (bauxite).

The sequence of mineral weathering proposed by Jackson *et al.* (1948)

indicated that the dominant minerals in soils in advanced stages of weathering are minerals of the kaolin, gibbsite, hematite, and anatase stability groups. Oxidation is considered positive in the weathering reaction equation, and reduction with a resultant aluminous product is considered a reversal of the reaction. The soils of the tropical regions are made up of these minerals, and according to Sherman (1949) a sequence of soils will develop for the dominance of each of these mineral groups, as for example: tropical red loams—kaolin stage; ferruginous laterite—hematite stage; bauxite laterite of Palau Islands—gibbsite stage; and titaniferous ferruginous laterite—anatase stage.

b. Kaolin Stage of Weathering (Stage 10). Increase of kaolin in soil mineral colloids as a function of increasing weathering intensity, followed by a decrease in kaolin with still further increase in weathering intensity or time, gives a well-defined maximum in the kaolin content of soils as a function of weathering (Jackson *et al.*, 1948; Tanada, 1950; Hseung and Jackson, 1952). Kaolin thus generally occurs in lesser amounts (up to about 15 per cent) in soils of temperate regions except when these soils are formed on unusually highly weathered parent materials. Kaolin often is the main constituent of the colloid in soils of warmer regions or in soils developed on older parent materials in the temperate region. With a still higher degree of weathering the kaolin content decreases again.

The kaolin content function of weathering is a continuous one. Thus Tanada (1950) found a decrease in kaolin content in the Hawaiian soils as a function of increasing rainfall. The rainfall was plotted on a logarithmic scale in order to make the decreasing function linear. One soil, developed under 15 inches of rainfall, did not fall on the regression curve, but seemed to suggest an increasing function at this low weathering intensity. The increasing function was nicely filled in by the finding of increasing amounts of kaolin with increasing weathering intensity in China soils (Hseung and Jackson, 1952).

It is to be recognized that the formation of kaolin in these soils and other soils to be considered may have taken place by geochemical weathering of the parent material, as brought out in Section I, 2. An extreme example of soil mineral domination by the parent material is reported by Peterson (1946b); the Gosport soil formed from Pennsylvanian shales and clays contains nearly pure kaolin clay, and its properties are strongly dominated by that mineral. He classified it as a Gray-Brown Podzolic soil developed in a Prairie soil region. Hosking (1940) found that kaolin formation was associated with granites under widely different climates, their corresponding soils ranging from Podzols to Sierozems. Kaolin was observed in Switzerland soils on old materials of Eocene

origin (Iberg, 1953), but 2: 1 layer silicates are common in Swiss soils. Kaolin occurs in Norway in weathered material which was protected from removal during the glacial period (Reusch, 1900; Strand and Rosenqvist, 1952).

Occurrence of kaolin in varying proportions with montmorin and other 2:1 layer silicates has been observed in numerous soils, suggesting a continuity in the occurrence of kaolin and montmorin, rather than clearly differentiated processes by which one or the other is formed. Soils in which the kaolin in proportion to montmorin is low (10–20 per cent) include Houston (Coleman and Jackson, 1946) and Fillmore and Miami (Wisconsin) (Jackson and Hellman, 1942), whereas an example of an approximate equal distribution between these two series of minerals is the Susquehanna (Alabama) (Coleman and Jackson, 1946). Kaolin constituted an appreciable percentage, ranging from about 15 to 60 and even 75 per cent, in the clay fraction of twelve soils from the Alabama locality (Pearson and Ensminger, 1949). Continuity of the weathering function is indicated by the occurrence of kaolin (stage 10) in complementary amounts with montmorin (stage 9), and vermiculite-like minerals (stage 8) in these soils. A distribution between micas, vermiculite, montmorin, and kaolin was noted in the Alamance, Bladen, and Norfalk soils of North Carolina (Coleman *et al.*, 1950). The less than 2-μ colloids of several ordinary and degraded paddy soils of Japan show evidence of kaolin and in some cases of montmorin and possibly illite (Sudo, private communication). Although differential thermal peaks were generally weak in all curves obtained, except for the endothermic peak between 100° C. and 200° C., the curve of the 1:1 layer silicates was most clearly recognized in each of the specimens.

The kaolin maximum stage of weathering is well illustrated by the Molokai, Wahiawa, and Kohala soils among the Low Humic Latosols of Hawaii (Sherman, 1949; Tamura *et al.*, 1953); by the red loams of eastern Australia (Stephens, 1949); by the red soils of India (Nagelschmidt *et al.*, 1940); by the Kweichu and Tsunjen soils of China (Hseung and Jackson, 1952); by the Greenville, Decatur, Dewey, Fullerton, Frederick, Chester, Cecil, and Manor soils of southeastern United States (Alexander *et al.*, 1939); and by the Catalina soil of Puerto Rico (Coleman and Jackson, 1946). Dominant kaolin was also noted in the Sierra, Redding, Aiken, Vina, and Keefer soils of California (Kelley and Dore, 1938; Kelley *et al.*, 1939a). Dominant kaolin was also noted in the Georgeville and Cecil soils of North Carolina (Coleman *et al.*, 1950). Occurrence of kaolin (including halloysite formed on red limestones) was reported in Indonesia (Hardon, 1939; Hardon and Favejee, 1939), and the dominance of one mineral type in each tropical soil was stressed.

Unmack (1944) found high kaolin with some illite and approximately 5 per cent of quartz, in a soil of Denmark. This material had highly plastic properties, and the occurrence of some interstratification of hydrated interlayers might be found with a more intensive investigation. Quartz and feldspar were present in the coarser fractions, and some vermiculite was suggested in the finer fraction. Marel (1950a) noted only halloysite and kaolinite as the clay minerals of lateritic weathering of rhyolitic rocks on the north east coast of Sumatra. Abundant kaolin was noted by Miller and Coleman (1952) in a red tropical soil and a humic forest soil of the highlands in Ecuador.

Clay beds of the Seto district, Aichi Prefecture, Japan, which appear to be secondary clays formed by selective sorting of altered granite, are composed largely of well-crystallized kaolinite (Sudo, private communication). Differential thermal analyses and electron microscopic examination verify the presence of kaolinite together with small amounts of hydrated halloysite.

The transition of the kaolin weathering stage maximum to the following (gibbsite) stage is shown by examples of kaolin mixed with portions of gibbsite and hematite in the colloids of the Fannin soil (Coleman *et al.*, 1950), Nipe soil of Puerto Rico (Jackson *et al.*, 1948), and Naiwa soil of Hawaii (Tamura, 1951). Unmack (1947) studied content of an old (Mesozoic) formation on the island of Bornholm (Denmark) and found that the clays were mainly kaolin whether they were formed *in situ* or deposited by sedimentation. The author states that he usually discarded the last centrifugate, a "very dilute suspension," consisting of particles less than 0.2μ. Some montmorin may have been lost by this procedure. One sample consisted of montmorin with some goethite. A sample of almost pure goethite was obtained from that locality also. Later studies (unpublished) showed that the TiO_2 present was in the form of anatase. A dominant amount of kaolin was reported in a soil derived from basalt in northwestern Tasmania (Shearer and Cole, 1939–1940b). This soil also contained 22 per cent of Fe_2O_3.

Differential thermal curves of Japanese soils derived from altered, bedded pumice deposits show minerals of the kaolin-allophane transition (Sudo, private communication) in soils described by Kawamura and Harada (1932) and Harada (1933, 1935, 1943). Harada found that these beds of pumice soil varied from about 0.5 to 2 m. in thickness. The transition to allophane (stage 11) was shown by the fact that every specimen of the uppermost bed (Kanuma soil) showed a differential thermal curve indicative of allophane (Sudo, private communication; Sudo and Ossaka, 1952; Sudo *et al.*, 1952) with no other peaks. A specimen of the underlying "Imaichi soil" also indicated the allophane-type mineral.

Several samples of the "Imaichi white clay," however, found in deeper-seated zones, revealed curves corresponding to hydrated halloysite (Sudo and Ossaka, 1952). Sudo considers (private communication), on the basis of differential peak characteristics, that the "Imaichi white clay" may well bear a mixture of hydrated halloysite and allophane.

c. Gibbsite-Allophane Stage of Weathering (Stage 11). The gibbsite–allophane stage of chemical weathering refers to the occurrence of a maximum in the distribution curve at stage 11 when mineral percentage is plotted against weathering stages of the weathering sequence presented in Section II, 1c. The inclusion of allophane with gibbsite is after the findings of Tamura (1951; Tamura *et al.,* 1953) of an amorphous aluminosilicate in fairly high abundance associated with certain highly weathered tropical soils of Hawaii.

The transition from the kaolinite to the gibbsite maximum wherein the two stages appear simultaneously has been observed in the Fannin and Rabun soils of North Carolina (Coleman *et al.,* 1950), in the red and yellow earths (Latosols) of South Africa (Merwe and Heystek, 1952), in the Cook Island Latosols (Fieldes *et al.,* 1952), and in eastern Australia (K. Norrish, personal communication). Often, however, kaolin family minerals are found in predominating amounts in the absence of detectable gibbsite, as in the Cecil soil of Wake County, North Carolina (Coleman *et al.,* 1950), the Cecil soil of Alabama, and the Catalina soil of Puerto Rico (Coleman and Jackson, 1946). Likewise, gibbsite and allophane occur in the virtual absence of kaolin minerals, for example, in the Hydrol Humic Latosols of Hawaii (Tamura *et al.,* 1953) as well as in the weathered rock beneath several Hawaiian Latosols.

Alexander *et al.* (1942) reported gibbsite occurring in varying proportions with kaolin in soils of southeastern United States. The gibbsite formed from aluminous hornblende, plagioclase feldspar, epidote, and biotite (from a muscovite–biotite shist), and sometimes appeared as a layer on rock surfaces.

The Tuerkuan Latosol of China contained 25 per cent of gibbsite in the fractions less than 5μ (Hseung and Jackson, 1952). This soil was derived from limestone. The kaolin content was only 9 per cent, and the hematite content was 23 per cent, thus giving a distribution curve at stage 11 of weathering, in accordance with the weathering sequence principle (Jackson *et al.,* 1948). Small amounts of gibbsite occurred in the Tsunjen red earth and the Yatzei "Podzol" of China.

The occurrence of the Arkansas bauxite is described by Mead (1915); large masses of nepheline syenite were intruded into folded Paleozoic rocks and changed to gibbsite and kaolinite. Two general classes of bauxite were recognized: namely, (1) bauxite in place, a residual prod-

uct of surface weathering of syenite grading downward into kaolin, in turn grading into syenite; and (2) transported bauxite, interstratified with Tertiary gravelly sediments. Behre (1932) proposed that weathering of these deposits was effected by sulfide waters derived from overlying lignite. Bramlette (1936) considered that they developed by normal weathering under hot humic conditions existing in early Eocene times, abundant vegetation having contributed to the reducing conditions and removal of iron to a lower depth. This description is similar to that of the formation of the aluminous Hydrol Humic Latosols of Hawaii (Sherman, 1952b). Thus bauxite forms in wetter parts of the tropical regions where oxidative conditions are not suitable for the stabilization of iron oxides.

Takeuchi (1942) studied a number of bauxites by X-ray diffraction methods and found that the bauxite from Haiphong, French Indo-China, consisted mostly of diaspore. Bauxites from the Dutch East Indies, the Palau Islands, and Malaya were made up dominantly of gibbsite. Boehmite was the hydrated aluminum oxide mineral in a bauxite from Montpellier, France. Chhibber and Misra (1941–1942) reported the chemical analysis of bauxite, one with 67 per cent Al_2O_3, and another with a high content of titanium oxide—a titaniferous bauxite. Goldich and Bergquist (1947) have reported the analysis of a bauxite having 5 per cent kaolinite, 60–70 per cent gibbsite, and 20 per cent hematite—a ferruginous bauxite. Sherman (unpublished) analyzed a comparable ferruginous bauxite collected in the Palau Islands.

Knecht (1945) from his studies of the genesis of concretionary bauxites in Brazil came to the conclusion that its development came in four progressive stages: (a) decomposition and complete leaching of parent material; (b) formation of a friable kaolin having a high content of iron oxide; (c) formation of colloidal aluminum hydroxide and hydrated aluminum silicate; and (d) decomposition to free hydrated aluminum oxides and soluble silica. He felt that heavy seasonal rainfall, warm climate, and a heavy vegetation were essential to the accumulation of the aluminum oxides. Chhibber (1946) has found that bauxite will develop on flat plateau-like hills under a tropical monsoon climate. Bauxite, according to his work, develops in a warm climate where there is gradual percolation of water and a high retention of water.

Utescher *et al.* (1948) from their work in the coastal areas of Cameroon found that bauxite formation occurs under high rainfall and high temperature. They also found that bauxite is not formed by primary silicates but comes from the weathering of layer silicates. According to Meulen (1949), bauxite is formed by the decomposition of kaolin minerals.

Boehmite, AlOOH, was found in the less than 2-μ fraction of the yellow sand of a fossile Podzol in the Netherlands, formed in the moist Atlanticum period (about 5500–2500 B.C.) and in the dry, hot Subboreal period (2500–800 B.C.) which followed the former (Marel, 1949). Apparently this mineral was formed by dehydration of the flocculated aluminum hydroxide gel which occurs in the yellow sand. Carroll and Jones (1947) observed in lateritic soils of western Australia an aluminum oxide mineral which was in their opinion boehmite or diaspore. This mineral was formed by partial desiccation of gibbsite during a recent very arid, hot period following the humid climate in which the Laterite itself originally was formed. Jackson (unpublished) found that one half of the aluminum of Haitian Latosol was in the form of boehmite and the other half was in the form of gibbsite. Approximately 15 per cent hematite occurred with the aluminum minerals. This finding was a part of the basis of inclusion of boehmite in stage 11 (Jackson *et al.*, 1948).

Allophane was described by Ross and Kerr (1934) as being essentially an amorphous solid consisting of silica, alumina, and water in varying ratios. Dehydration curves of the material are of a continuous nature characteristic of a material in which the water is sorbed and not as hydroxyl. Ross and Kerr point out the common association of allophane with halloysite.

Baren (1941) noted on the west coast of Sumatra the occurrence of a "silica-gel" later shown (personal communication) to be amorphous to X-rays; this may have been an allophane material. Sudo (1952) applied differential thermal analysis to study of the less than 2-μ fraction of surface and subsoils of "Kwanto loam," a soil derived from volcanic glass in Japan, whose mode of occurrence and origin has been described by Kawamura and Harada (1932), Harada (1933, 1935, 1943), and Nakao (1930–1937). The thermal curves obtained revealed the presence of allophane as the only mineral with the exception of small amounts of limonite. He also observed that a specimen of this soil colloid treated with piperidine exhibited an extremely strong and continuous reaction from about 200° C. to about 800° C., which was interpreted as an indication of the presence of allophane. Colloids from deeper horizons of the "Kwanto loam" suggested the presence of kaolinite or hydrated halloysite in addition to allophane (Sudo, private communication). Some soils dominant in kaolin gave thermal indication of small amounts of admixed gibbsite, generally in shallow zones, or montmorillonite, in deeper-seated zones. Evidence of an amorphous colloid with kaolin was found in degraded paddy soils.

Sudo feels that allophane may be formed in swampy regions by leach-

ing of pumice fragments or volcanic ash by weak acidic water containing humus. In such a poorly drained environment, the water may be gradually neutralized and finally made alkaline by infiltrating bases. Silica, then, may be leached under this alkaline environment, leaving a residue of allophane.

Allophane was identified in amounts of approximately 30 per cent in the fraction less than 0.2μ of two Hydrol Humic Latosols (Tamura *et al.*, 1953). Gibbsite constituted 25–35 per cent of the clay fraction of these soils. Associated with the above two stage 11 minerals was from 10–20 per cent of goethite, 5–10 per cent of montmorin, and a little mica and quartz. Gibbsite constituted 15–20 per cent of the clay fraction of the Humic Latosol in association with 15–20 per cent of kaolin, 20–25 per cent of hematite, and 10–20 per cent of goethite. Small amounts of montmorin and other 2:1 layer silicates were present. A succession in mineral weathering stage was suggested by Tamura *et al.* (1953) of the three soil groups as follows: Low Humic Latosol, Humic Latosol, then Hydrol Humic Latosol (most advanced stage last).

d. Hematite–Goethite Stage of Weathering (Stage 12). The hematite–goethite stage of chemical weathering refers to the occurrence of a maximum in the distribution curve at stage 12 when mineral percentage is plotted against weathering stages of the weathering sequence presented in Section II, 1c. There is ample evidence of the formation of both hematite (Fe_2O_3) and goethite ($FeOOH$) as products of weathering, although in localities in which hematite is a prominent constituent of rocks, workers have not been sure hematite was a product of weathering. Hematite has been found by Tamura and the senior author (unpublished) in highly crystalline form in concretions of a soil from the Dominican Republic, and crystalline hematite is formed in many localities, as will be brought out in this section. The terms "hematite" and "goethite" will be employed in this writing only when the crystal species has been verified by means of X-ray diffraction. Otherwise, the term "iron oxides" will be employed.

In general, hematite occurs in dryer and more highly oxidized horizons usually nearer the soil surface, whereas goethite occurs more typically in wetter though well-oxidized zones, often in the subsurface horizons. These oxides occur in abundance in highly weathered soils which have not been subjected to highly reducing conditions. Assignment of them to stage 12, indicating a more advanced stage of weathering than gibbsite (stage 11), is done on the basis that oxidation is positive in the weathering reaction equation (Jackson *et al.*, 1948) and that iron oxide removal by reduction to cause concentration of aluminum-rich colloids is thus a reversal of the weathering reactions. Hough and Byers

(1937) and Hough *et al.* (1941) concur that alumina was more mobile than iron under Hawaiian conditions in which reduction was not a factor.

One of the most important observations of Campbell (1917) is that iron oxide accumulates in that portion of the soil which is alternately dry and wet owing to the oscillation of the water table. The hydrated aluminum silicates and possibly free alumina accumulate in the zone which is continuously wet. Thus in the equatorial regions which have alternating wet and dry conditions, one would expect to find the ferruginous Laterite, and in the tropical rain forest one would expect to find tropical soils rich in aluminum. This has been recently suggested by Sherman (1952b) in his report on the genesis of alumina-rich clays of the tropical regions.

Campbell (1923) has shown that the deposition of iron oxides cannot take place below the permanent water table because oxygen is required in the process. He believes that true weathering can only take place in the presence of oxygen. Thus, the alternation of wet and dry seasons which causes the oscillation of the water table facilitates the development of the Laterite horizon by bringing ferrous iron into solution in the zone where its precipitation as ferric iron can take place. Resilication to form layer silicates does not take place with the temporary rise of the water table during the wet season even though the waters may contain soluble silica. It should be pointed out that Sherman (1952a) believes that resilication of alumina occurs under conditions of poor internal drainage where the water containing soluble silica remains in contact with the hydrated aluminum or iron oxides over a considerable period of time. It is not likely that the resilication of iron oxides will take place under these conditions, due to the susceptibility of ferric iron to reduction.

There are many reports of the occurrence of substantial amounts of hematite and goethite in soils. Coleman and Jackson (1946) noted crystalline hematite in amounts of 5–10 per cent in the clay fraction of Cecil soil of Alabama. Coleman *et al.* (1950) noted 5–30 per cent crystalline hematite in the clay fraction of Alamance, Georgeville, Cecil, Fannin, and Rabun soils of North Carolina. Tamura (1951) noted up to 60 per cent of goethite and hematite in various horizons of the Naiwa soil of the Ferruginous Humic Latosols. He noted crystals of hematite of silt size, as measured by the diffraction method for crystal size. Sherman *et al.* (1949a) previously reported extremely high iron-oxide contents of this soil, and Sherman (1949, 1950) has reported on the systematic accumulation of iron oxides with increasing weathering. Fieldes *et al.* (1952) reported 30–75 per cent iron oxides in clay fractions of soils of the Cook Islands, of which part was goethite. Hseung and Jackson (1952) reported 10–23 per cent of free oxides in soils of China, the higher

content occurring in a Latosol. Tamura *et al.* (1953) reported 20 per cent of hematite and goethite in the Low Humic Latosols, 36 per cent in the Humic Latosols, and 16–19 per cent in the Hydrol Humic Latosols of Hawaii.

According to Marel (1951), gamma Fe_2O_3 is formed in nature by slow reduction and afterwards oxidation of lepidocrocite (gamma FeOOH) or limonite (i.e., goethite, alpha FeOOH) particles or concretions rich in organic matter. Thus gamma Fe_2O_3 may be a common mineral in sediments (soils) rich in iron and organic matter, such as the brown-red peaty soils in the Netherlands. It was further found that iron hardpans in peats which are formed by oxidation of ferrous-organic compounds by oxygen of air consist mostly of lepidocrocite (gamma FeOOH). Some of these iron hardpans are so vast that the material is sold to gas plants as adsorbents. Iron hardpans which are formed by oxidation of ferrous bicarbonate by oxygen of air, however, consist mostly of limonite (i.e., goethite or alpha FeOOH). Iron hardpans containing lepidocrocite are found also.

Mackenzie *et al.* (1949) reported a "low temperature hydrated iron oxide" coating on a soil colloid of Scotland which gave a sharp exothermic peak by differential thermal analysis. Hardon (1940) showed a correlation of water loss between 200° C. and 300° C. and the content of total iron oxide, and concluded that goethite was common in soils of Indonesia. Hamilton (1948) found hematite rather than goethite in soils of the Celebes, Borneo, and Sumatra, in association with kaolin and gibbsite.

e. Anatase-Leucoxene Stage of Weathering (Stage 13). The anatase–leucoxene stage of chemical weathering refers to the enrichment of titanium oxides in the soil as weathering approaches the highest degree, in accordance with the weathering sequence principle outlined in section II, 1c. Included with anatase in weathering stage 13 are leucoxene, which is hydrated amorphous titanium oxide (Tyler and Marsden, 1938; Carroll and Woof, 1951), both the products of the weathering synthesis mechanism, and ilmenite, brookite, and rutile of the weathering residue mechanism. Zircon can be considered a part of the most resistant mineral suite, although it has not been reported in abundance in the colloid fraction. Accumulation of titanium in the last stages of weathering occurs under intense leaching with moderately good oxidation. The highest concentration of titanium occurs under conditions involving enough reduction periodically to remove the iron oxides (Sherman, 1952a). McGeorge (1912) and Sherman (unpublished) have found Latosols in Hawaii which contain approximately 35 per cent titanium oxide, but

weathering products which consist mostly of titanium oxide have not been reported.

The accumulation of titanium oxide to concentrations in the range of 2.5–25 per cent has been noted by Sherman (1952a). It commonly occurs in association with an iron-oxide content of 45–55 per cent, in line with the normal distribution curve between the anatase maximum and weathering stage 12 which includes iron oxide. High contents of iron and titanium in soil surface horizons were reported by Sherman and Kanehiro (1948). Separated mineral fractions from the Naiwa family of Humic Ferruginous Latosol (Fujimoto and Sherman, 1948) in the high specific gravity fraction of the surface horizons contained 35.8 per cent TiO_2. A clay fraction contained 35.4 per cent TiO_2. The diffraction patterns of these soil fractions showed the presence of anatase.

Enrichment of TiO_2 was shown in a Latosol developed on basalt in New South Wales (Carroll and Woof, 1951). The original basalt contained less than 1 per cent of TiO_2, but the soil contained up to 18 per cent TiO_2. Soils of the Canary Islands contain up to 10 per cent of titanium oxide, as ilmenite and rutile (Castro, 1945). The content of titanium oxide is 5–10 per cent in the purple-red soils of Brazil (Setzer, 1948). The titanium oxide content of the 5-μ fraction of the Tuerkuan Latosol of China developed from limestone was 5.6 per cent, and the titanium content increased functionally with increase of weathering intensity in China soils (Hseung and Jackson, 1952).

Like iron oxide, titanium oxides are subject to removal by pedogenic processes, particularly processes induced by reducing conditions (Sherman, 1952a). Iron oxide is more readily reduced; hence, the first effect of reduction is an increase in the TiO_2 content to a maximum through removal of iron. Further increase in wetness and reducing conditions causes a chemical reduction of titanium, its leaching, and a resultant lower percentage of titanium oxide in the soil. In Hawaii, this results in the development of the Hydrol Humic Latosol, high in the hydroxides of aluminum.

The Hydrol Humic Latosol is the stage 11 equivalent of the A_2 horizon of Podzols (stages 6–10), in each case corresponding to leaching under reducing conditions (weathering reversal).

Accumulation of TiO_2 in both Podzols and Latosols in the surface has been reported (Joffe and Pugh, 1934). The TiO_2 was attributed to the presence of the mineral ilmenite, and this same view is expressed by Hough and Byers (1937).

Hough *et al.* (1941) presented a hypothesis on the accumulation of TiO_2 by a process of "podsolization." His hypothesis is based on the following conditions: (a) the parent materials of Hawaiian soils have a

high content of titanium and contain practically no quartz; (b) titanium exists as the two primary minerals, rutile and ilmenite, which are considered to be the most resistant minerals in the soil to weather. He further assumes that these two minerals are not attacked by weathering processes; and that (c) in the absence of quartz other resistant minerals such as ilmenite and rutile would accumulate in the surface horizon of the soil. If one assumes that the titanium minerals have not been weathered or translocated, calculations will show that silica, iron, and aluminum have been translocated in a manner similar to that found in Podzols.

Sherman (1952a) found titaniferous-ferruginous concretions in Hawaiian soils which establishes these soils as the product of "laterization" and not "podsolization." Sherman (1949, 1950) has presented data which indicated that the titanium in these soils has accumulated in the surface horizons by ascending waters. The presence of anatase shows that a synthesis mechanism operates in addition to the residue enrichment mechanism proposed by Hough *et al.* (1941). Titanium in these titaniferous-ferruginous laterite crusts is found to exist as both anatase and ilmenite. The former is brought to surface in ascending waters, and the latter may have escaped the attack of weathering processes or may be secondary ilmenite formed during the dehydration of lepidocrocite and leucoxene in close proximity in the surface horizon.

V. Weathering Release of Nutrient Elements from Soil Minerals

The weathering release of nutrient elements from soil minerals has been the subject of intensive investigation for many years. The earlier experimental measurement of release was that of exhaustive field cropping of soil without fertilization, followed by analysis of the crops. This was followed by a series of intensive studies by greenhouse methods of the "nutrient supplying power" of soils. In general it was found that a considerable number of crops could be obtained, but a decreasing yield and eventually crop failure resulted with this method. Various laboratory methods have been developed to estimate the fraction of a given nutrient in a given soil that is slowly or moderately available.

Different minerals have been shown to have greatly different rates of availability of their nutrient ions. Soil content of a given mineral series such as mica or feldspars has been correlated with soil supplying power of a nutrient or soil productivity. Jeffries *et al.* (1952) noted a correlation of productivity rating of soils of Puerto Rico with the soil content of feldspars.

In both the tropic and temperate zones, efforts of farmers and agronomists have to a considerable extent been devoted to the development of

plants and systems of soil management which would exploit with maximum efficiency the nutrient elements released from soil minerals by chemical weathering. Improvement in rooting vigor and selection of varieties which are "tolerant to" (i.e., yield well in spite of) soil acidity or low nutrient levels, for example, are ways of exploiting this source of nutrients. Crop rotation, patch agriculture (in the tropics), and paddy culture are other examples. Soil treatments have been devised to enhance the availability of nutrient ions of native soil minerals. In the latter category particularly has been the treatment of the soil with ground limestone to release some of the phosphorus tied up with the trivalent metallic ions.

1. General Level of Soil Fertility Is Related to Weathering Stage

In both the temperate and tropical zones, the general level of soil fertility is determined by the weathering stage of the minerals present. This idea is often expressed in terms such as "inherently fertile soils," "old infertile soils," "highly leached soils," and even "senile" and "dead soils." Soils containing minerals of the early weathering stages, such as those which have recently undergone glaciation in the temperate zone, soils that have recently received ash fall in the tropical zone and soils that continually receive alluvium containing minerals of intermediate or early weathering stages, are generally recognized as being fertile soils.

a. Influence of Mineral Content in the Temperate Zone. Fertility of soils in the temperate zone is dependent not only on relief, organic content, and texture but also on the kinds of minerals in the soil. Baren (1934, 1935) concluded that the nutrient supplies of soils of the Netherlands were correlated with the content of feldspars and biotite. A study by Hawkins and Graham (1951) of ten widely different Missouri soils showed that the percentages of potassium feldspars and plagioclase feldspars occurring in the silt was in direct proportion to the fertility levels and in inverse proportion to the stage of weathering. In Wisconsin and Indiana, soils formed on the older tills are much less fertile than those formed on the latest glacial till. For example, the potassium supplying power was only one-third as high for the Almena soil (early Wisconsin till) as for Miami soil (middle Wisconsin till), according to work of Evans and Attoe (1948).

b. Influence of Mineral Content in the Tropical Zone. In tropical soils, the weathering of the minerals progresses at a rapid rate. The bases are released in rather large quantities in the early stages of weathering. Baren (1941) concluded that the fertility of tropical soils of Sumatra was correlated with their content of primary minerals. Mohr

(1944) has divided weathering into five stages: fresh, juvenile, virile, senile, and laterite stages. Plant growth increases rapidly in the juvenile stage and reaches its maximum in the early part of the virile stage, because at this point the nutrient elements are being released to the soil solution at a maximum rate and the level of base saturation of the soil is at a maximum. The soil according to Mohr is classified as a brown earth. These soils have a high content of 2:1 layer silicate minerals. Plant growth begins to decrease at the end of the virile stage and decreases rapidly as the senile stage develops. The end of the virile stage is approximately at the point one would expect to find the peak of kaolinization. From that point on, the kaolin is succeeded by the hydrated free oxides. Plant growth all but ceases with the development of the laterite stage.

The natural productivity of the soils in the early stages of weathering has been observed by other workers. Hardy (1939) states that volcanic ash soils develop as rapidly as or more rapidly than they erode. Their productivity is high. Edelman and Beers (1939) have reported that infertile soils can be rejuvenated by application of volcanic ash. Edelman (1946) states that the young soils on both volcanic ash and lava are very fertile. Edelman and Beukering (1948) state that in the tropics the young soils developed on volcanic ash are rich. Chevalier (1949) describes a similar relationship in Africa to that described by Mohr in Java.

In general the most productive soils in the tropical regions are the brown soils and the less weathered of the tropical red loams. In these soils, the chemical weathering stage passes from soils having a mixture of montmorin and kaolin minerals to the peak of kaolinization. It is at this point in soil development where one obtains the best combination of high base saturation and physical properties. It is on this type of soil that the great agricultural development has occurred in the Hawaiian Islands. This would be comparable to Mohr's (1944) point of maximum growth.

As leaching progresses, with further mineral weathering, the supply of available nutrient elements decreases to a point at which plant growth becomes limited. Aubreville (1947), Chevalier (1948, 1949), Pendleton (1941), Scaetta (1938), and Edelman (1946) describe the decrease in vegetation which develops during the senile stage of soil development and lack of vegetation on the laterite crust. In almost every case the loss of vegetation precedes the formation of the crust, and thus the loss of vegetation must be partly due to the low level of plant nutrients. It is true also that the physical properties of the crust are not conducive to plant growth.

2. Weathering Release of Nutrient Ions from Soil Minerals

The nutrient ions to be considered in connection with weathering release from soil minerals include potassium, calcium, and magnesium among the common cations (and associated nickel and chromium among the toxic elements); phosphorus, nitrogen, and sulfur among the common anions; iron, manganese, copper, zinc, boron, and molybdenum among the minor elements.

a. Weathering Release of Potassium. The chemistry of soil potassium has been reviewed through 1951 previously in this publication (Reitemeier, 1951) and elsewhere (Reitemeier *et al.*, 1951). The water collected from lysimeters (Demolon and Bastisse, 1946) filled with sieved granite showed more potash released per year than those filled with soils. Since fresh rock has a low base exchange capacity, little of the released potash could be held in exchangeable form as it is held by soil.

Rouse and Bertramson (1950) showed a correlation of the 10-A. diffraction intensity (mica content) of soil clays with the potassium supplying power of several Indiana soils, and Phillippe and White (1952) showed a correlation of microcline content of the silt with the acid-soluble potassium level in twelve Indiana soils. Expansion of mica interlayer spaces with weathering has been discussed in Section II, 1c in connection with the weathering sequence, whereby vermiculite and montmorin appeared to weather from mica. Barshad (1948, 1950) showed in the laboratory that magnesium, calcium, and sodium would open up the interlayers of mica to the 14-A. vermiculite spacing by slow exchange, and thus demonstrated a likely mechanism of release of mica potassium to crops in available form. White (1951) showed that treatment of an illite with magnesium salt solutions gave rise to a 17.8-A. spacing (in the presence of a lessened 10-A. diffraction intensity), thereby further strengthening evidence of montmorin formation during potassium release from some kinds of mica.

Pratt (1952) showed a high release of potassium from the coarse clay fraction of thirteen Iowa soils; the mica content is known to be high in the coarse clay fraction of soils in that locality. Kolterman and Truog (1953) found that large amounts of potassium could be released to exchangeable form by the heating of soils and micaceous clays to 300° C. while saturated with ammonium. Graham and Turley (1948) showed weathering release of nonexchangeable potassium to forms available to soybeans.

Marel (1947) found that andesine occurring in the clayey andesitic soils of the coastal regions of Java could deliver sufficient potassium to sugar cane, which removes about 200–250 kg. of K_2O per hectare in

about 130 tons of stalks. In the tea district of Korintji (west coast of Sumatra) situated on soils of andesitic basaltic origin, potassium deficiency disease appeared in the plantations. The reason is that soils developed from basic rock are so poor in potassium that they can not deliver even 40 kg. K_2O per hectare, which is needed to obtain an annual yield of about 1,400 kg. of dry leaves per hectare. These soils, however, contain plenty of calcium, magnesium, and phosphoric acid. Soils of acid rock origin, such as rhyolitic soils, however, are rich in potassium but poor in calcium, magnesium, and phosphoric acid.

Michio Ota (Tokyo University) studied the agricultural values of certain minerals containing potassium, such as biotite, orthoclase, green tuff, and jarosite (unpublished). Among these materials, he found that jarosite shows the most agricultural value in a paddy soil in the summer. The jarosite used is found in association with a limonite deposit of the Suwa Mine, Nagano Prefecture, formed in a hot spring, and its potassium is not soluble in water. Ota confirmed that hydrogen sulfide, which is commonly produced by the reducing environment in a paddy soil, acted upon jarosite, combined with the iron of this mineral, accelerating its decomposition and releasing its potassium.

b. Weathering Release of Calcium, Magnesium, Chromium, and Nickel. Calcium and magnesium release from limestone and dolomite subsoils is a matter of common knowledge and frequently prevents deficiencies of these elements in soils which are otherwise low in exchangeable calcium and magnesium. Graham (1941a) showed that hornblende and augite released calcium at a rate thought to be sufficient for soybeans. Marel (1947) found that weathering of amphibole, hyperthene, and biotite supplied sufficient calcium and magnesium for crop growth in Sumatra. Marel (1950b) observed that weathering of minerals in temperate climate in the Netherlands is much slower than he had noted in the tropics. He found, however, that in the climate of the Netherlands, dolomite could supply enough magnesium and glauconite, enough potassium and magnesium to oats (cultivated in Mitscherlich pots) to obtain optimum harvests. Biotite could not supply sufficient potassium and magnesium in this climate to obtain optimal growth of the oats in the Mitscherlich pots.

The release of calcium by weathering of anorthite and other plagioclases was shown by Graham (1941a, 1941b, 1942). The weathering rate was shown to be hastened by the presence of hydrogen-saturated clays, and was significant to soybean nutrition. The pH of hydrogen clay rose in the presence of anorthite from 3.3 to 5.7 in 107 days. The amounts of nutrient release had also previously been demonstrated to be significant to plant growth (Albrecht *et al.,* 1938; Graham, 1939).

Release of magnesium from soils high in the mineral chlorite gives rise to excess of magnesium as compared to calcium, the areas sometimes being known as the "serpentine barrens." The literature on this subject is reviewed by Robinson *et al.* (1935); their analysis of soils and plants indicate toxicity of chromium and nickel in many infertile serpentine soils. Molybdenum deficiency is also associated with the serpentine barren soils (Walker, 1948; R. P. Stout, lecture at the University of Wisconsin, 1952).

Chromium is often found in very appreciable quantities in the tropical ferruginous soils. Simpson (1916) found the content of chromium oxide of ten western Australian laterites to range from nil to 5.3 per cent. Soils having a high content of chromium have been reported in South Africa by Merwe and Anderssen (1937) and in Samoa by Birrell *et al.* (1939). In the former, the soluble chromium is so high in the soil as to be toxic to plants.

Chang and Sherman (1953) have found evidence to support the accumulation of appreciable amounts of nickel in the soils of the Low Humic Latosols of the Hawaiian Islands. The nickel has been released in the weathering of the olivine-rich basalts. The available nickel content of these soils is high and approaches levels which may be toxic to plants.

c. Weathering Release of Phosphorus. The native phosphorus of soils, aside from that in the organic matter, which may be half to three-fourths of the total, occurs in soils largely as the mineral apatite, $(Ca_{10}(PO_4)_6(F,OH)_2$, and as a family of iron and aluminum hydroxy phosphates. As weathering of the mineral phosphates proceeds, small increments of the phosphorus go over into solution and adsorbed forms from which crops take it. Moderately rapid release of native mineral phosphate appears to take place in soils of very slightly acid reaction (Truog, 1916). The calcium phosphate of alkaline soils is only slowly available, except as the soil is acidified by the application of sulfur or other acid-forming material. Marel (1947) found that volcanic glass, hypersthene, and anorthite contained sufficient apatite inclusions and weathered fast enough to supply enough phosphorus for crops in Sumatra.

Phosphorus in hydroxy salts of aluminum and iron appears to be very slowly released to crops if the soil is highly acid; however, when an acid soil is amended by the application of finely ground limestone or the acidity decreased in other ways, phosphorus is often released from minerals at a significant rate for crop growth. Snider (1934) reported that the addition of limestone to certain Illinois soils increased the solubility of the native phosphorus to such an extent that no additional yield responses were obtained from phosphate applications. Salter and Barnes

(1935), working in Ohio, reported constant wheat yields and increasing corn yields throughout thirty-two years without phosphate applications on plots which received adequate limestone, potash, and nitrogen fertilization in addition to manure. Without limestone addition, the yields steadily declined with the same treatments. Cook (1935) found that more phosphorus was extractable in dilute acid after several acid soils were limed than before. Dean (1938) reported that the amount of alkali-soluble inorganic phosphorus in some soils decreased significantly with increase in pH, but that the amount of weak acid-soluble (mineral) phosphorus increased with pH. Unpublished studies at the University of Wisconsin by O. J. Attoe and associates also indicate a marked increase in the availability of soil phosphorus as a result of liming acid soils.

d. Weathering Release of Nitrogen and Sulfur. Although the release of nitrogen is for the most part associated with organic matter of soils and is not concerned with mineral weathering, two aspects deserve mention. Nitrogen in fixed form occurs in igneous rocks in some abundance (Ingols and Navarre, 1952). Leaching of it in mountain springs yields an appreciable amount of fixed nitrogen. Although NH_4Cl occurs in volcanic materials, this is not the only source in igneous rocks, because fixed nitrogen is yielded by weathering granitic rocks long after soluble nitrogen would have been leached. Occurrence of ammonium ion in micas and vermiculites (Bower, 1951) could well account for the slow release of nitrogen salts from both basic and acidic rocks, as well as for the fixation of soil ammonium in slowly available mineral form.

Besides its occurrence as soluble salts in soils, sulfate occurs in soils as the moderately soluble mineral, gypsum ($CaSO_4 \cdot 2H_2O$), and the slowly soluble mineral, barite ($BaSO_4$). The latter mineral has been associated with infertility of soils by Robinson *et al.* (1950). Also it has been shown to be much more soluble in the presence of layer silicate colloids than in water (Bradfield, 1932). This is explained by the fact that the barium ion activity is decreased by the colloid to values lower than would be expected in a solution of the ions in contact with barium sulfate. This type of action by colloidal clay on barium sulfate solubility is closely akin to the action of hydrogen clay in weathering minerals, as shown by Graham (1941a, 1941b, 1942).

e. Weathering Release of Minor Elements. The weathering release of minor elements will be considered in relation to copper, zinc, iron, manganese, boron, and molybdenum. The possible relationships of soil minerals to the trace element status of soils have been reported. Thomas (1940) suggested that copper and cobalt are ordinarily associated with the more bâsic magmatic constituents, and that they are relatively rare in the feldspathic and quartzose minerals of the more acid igneous rocks.

Association of copper supply with soil mineral weathering is suggested by the frequent association of copper deficiency with organic soils (Harmer, 1946).

Wager and Mitchell (1943, 1950) indicated that the various trace elements are associated with several stages in differentiation and consolidation of the original rock material. Chromium and nickel are concentrated in the first rocks to solidify; vanadium in the early middle stages; copper and lithium in the later middle stages; and molybdenum, zirconium, thorium, lanthanum, and rubdium are concentrated in the last rock to solidity, i.e., granitic types.

Graham (1953) studied the relationship between soil mineral weathering and the trace element status of some Australian soils. He reported that the stage of weathering, as established by analysis for quartz, feldspar, and heavy minerals, was advanced for soils of known and suspected trace element deficiency, and was moderate to low in soils nondeficient in trace elements. High amounts of gibbsite were found in the 2- to 20-μ fraction of soils from areas demonstrated to be copper-deficient. Gibbsite was not found in any of the soils nondeficient in copper. Carroll (1944) noted a good correlation of the ferromagnesian mineral content of the sand fraction of some Australian soils with high to very high copper contents of subterranean clover grown on these soils. The occurrence of gibbsite in soils of demonstrated copper deficiency suggests, according to Graham (personal communication), the importance of minerals which could render some heavy metal plant nutrients unavailable, a subject which he believes might well be investigated further.

The weathering rates of several copper minerals (chalcopyrite, $CuFeS_2$; bornite, Cu_5FeS_4; copper glance, Cu_2S; malachite, $CuCO_3 \cdot Cu(OH)_2$) were investigated (Steenbjerg, 1943, 1951) by means of crop yield curves and by measurement of the copper absorbed by barley plants grown in pots in a soil very deficient in copper. The relative number of copper atoms on the surfaces of the minerals added to the soil were calculated. The size of applications was adjusted to give the same number of surface copper atoms in the different copper minerals. In this way it is possible to observe how plants react to copper added in copper minerals with different crystal structures.

It was shown that there exist two main types of weathering of sparingly soluble fertilizers (minerals) added to, or occurring in, the soil. The two types are termed the "copper type" and the "potassium type." Owing to small absorption and absence of leaching, the products of the copper type of weathering accumulate in the soil, and the physical and chemical properties of the newly formed compound or compounds rather than those of the original mineral become the dominant factor in nutrient

availability to plants. On the other hand, with the potassium type of weathering, particularly of K minerals or slightly soluble N compounds, the products are rapidly removed from the mineral added owing to the high degree of absorption and leaching; under these conditions, it is the crystal structure and weathering rate of the original mineral that determine nutrient absorption and dry matter production.

Zinc is thought to occur in soil minerals mainly as an isomorphously substituted cation in an octahedrally co-ordinated position normally occupied by magnesium (Elgabaly and Jenny, 1943; Elgabaly, 1950). An association of zinc deficiency with the mineral content of soils is suggested by the occurrence of zinc deficiency on organic soils (Ellis, 1945).

Iron occurs in soils in the minerals hematite, ilmenite, magnetite, and goethite; in x-amorphous hydrous oxide colloids and coatings; and in isomorphously substituted positions in micas and other 2:1 layer silicates. Availability of iron to crops rests largely on its being reduced to the more soluble ferrous form, just as its migration during weathering depends to a considerable extent on its being reduced. Kliman (1938) showed that plants had a means of reducing iron in the environment of the root hairs. Chapman (1939) demonstrated the release of iron from finely ground magnetite through its uptake by citrus seedlings.

In the Hawaiian Islands, iron deficiency occurs on some soils even though they contain large quantities of free iron oxides. According to Johnson (1917, 1924), the high content of manganese dioxide in the soils prevents the assimilation of iron by the plants. It is suggested that manganese of the soil oxidized the iron to the ferric form which was unavailable to plants. Sherman and Fujimoto (1946, 1947) have evidence which attributes the iron deficiency of the plants to an unfavorable manganese: iron ratio in the plant. They point out that both manganese and iron exist in an oxidized state in the soil and that conditions other than the content of manganese in the soil control the oxidation-reduction environment of the soil.

Manganese occurs in the soil as hydrous manganese oxides, pyrolusite, manganite, and braunite. The solubility of the various manganese minerals in the soil is very low, especially that of the hydrous manganese oxides. According to Sherman and Harmer (1943), the plant can utilize only the manganous ion, and thus available manganese will include the water-soluble manganese, the manganese adsorbed to the soil colloids, and the manganic manganese which can be reduced at the root surface. Fujimoto and Sherman (1948) have found that the available manganous ion will increase in the soil with an increase in conditions favoring reduction of manganic ion or dehydration of the colloidal hydrated manganese

oxides. Leeper (1935) has classified the manganese in soils into the following forms: (a) manganous manganese; (b) the colloidal hydrated manganese dioxide; and (c) inert manganese dioxide. He proposed a hypothesis in which the soil manganese would exist in an equilibrium which can be expressed by the following equation:

Manganous manganese $\rightleftarrows$ hydrated colloidal MnO_2 $\rightleftarrows$ inert MnO_2. Leeper (1947) has modified this equation to include Mn_2O_3, Mn_3O_4, and MnO_2 in the term "manganic oxides." Sherman and Harmer (1943) have shown that there is an equilibrium between manganous and manganic manganese in the soil and that the direction of the equilibrium is determined by soil reaction, the oxidation-reduction conditions of the soil, and soil moisture conditions. Likewise, Fujimoto and Sherman (1948) have concluded from their work that two processes influence the availability of manganese in the soil other than soil reaction and that they are, first, the oxidation-reduction conditions and, secondly, the conditions for hydration and dehydration of the manganese oxides. In very acid soils, hydrated manganese oxides will not form. If the soil solution contains any appreciable concentration of hydroxyl ions, the hydrated oxides will form readily in the manner described by Bertrand and others whose work is quoted in Mellor (1932). Thus acid soils will have a high content of available manganese, and alkaline soils will have a low content of available manganese. Sherman and Harmer (1943) and Fujimoto and Sherman (1948) have shown that if the hydrated colloidal manganese oxides are dehydrated, they become soluble. It is proposed that the dehydrated manganese oxides $(MnO)_x \cdot (MnO_3)_y \cdot (H_2O)_z$ break down to its component parts. These workers feel that the release of manganese in the soil is due to physical and chemical conditions. Leeper (1947) and Dion and Mann (1946) have presented data to show that biological factors may be responsible for the reduction of manganic manganese in the soil. Fujimoto and Sherman (1948) and Dion and Mann (1946) have developed manganese cycles in soils which are very similar, except that the former based their cycle on the physical and chemical conditions of the soil, whereas the latter based their cycle on biological conditions.

In certain soils there is a definite accumulation of pyrolusite in concretionary form. According to Sherman *et al.* (1949b), concretions of pyrolusite will form in predominantly dry soils which are appreciably wet during some season of the year. These workers have found that the manganese is reduced during the wet season and is precipitated during the dry season. The concretionary deposition occurs around small nuclei, pores or small holes in soil, around aggregates, and on the surface of

roots. Living plants with large pyrolusite concretions around the root were found by these workers in the Hawaiian Islands.

The chemistry of soil boron has been reviewed previously in this publication (Berger, 1949); the consideration of its release by weathering will therefore be brief. Of the total boron in soils, approximately half was attributed to tourmaline and allied resistant borosilicates (Whetstone *et al.*, 1942). The other half is fixed in mineral and organic forms —forms which are more closely related to the boron supply important to crops. Whetstone *et al.* (1942) estimated the tourmaline in soils on the basis of the soil boron insoluble in boiling 85 per cent phosphoric acid. The 200 soils analyzed averaged 30 p.p.m. of total boron, of which 17 p.p.m. of boron was insoluble in the acid treatment and attributed to tourmaline. Weathering release of boron from tourmaline and like minerals of this degree of insolubility would be expected to be slow.

Soils of known molybdenum deficiency and suspected molybdenum deficiencies were characterized (Graham, 1953) as being highly weathered. They contained a very high percentage of quartz and extremely low amounts of feldspars. A very low amount of ferromagnesium and ferrocalcium minerals was found in some of the samples. However, molybdenum-deficient soils in general were characterized by a very small amount of weatherable minerals in the heavy fraction.

3. Systems of Utilization of Soil Mineral Weathering Sources of Nutrients

The agricultural development in the tropical as in the temperate regions has been along both primitive and modern lines. There is a tremendous contrast between the intensive agricultural crop production found in the Hawaiian Islands and the Dutch East Indies by the addition of mineral fertilizers, and the "patch agriculture" practiced so extensively in the tropical regions. There are two entirely different philosophies in soil management behind these very different systems of agricultural production. Although most people think of the tropical agriculture as being the ultimate of self-sufficiency, it is actually fraught with many problems of crop nutrition. One must realize that soils in the tropics range from youthful to senile in their stage of development. The youthful soils such as the soils of the "red and black complex" and tropical red loams are productive because of their high base status and the presence of the montmorin and kaolin minerals.

In the old soils of the humid tropics, the condition is very different. Under these conditions the soils are progressively losing their bases. The progress of this leaching process is retarded by the native vegetation in that it is constantly returning the bases from the subsoil to the

surface by the fall of leaves to the surface. As long as the forest can maintain an adequate base circulation from the subsoil, through the tree, to the leaves and finally to surface soil in the leaf fall, the soil remains productive. When the forest is removed the whole cycle is interrupted with the result that marked changes occur in the physical and chemical properties of the soil. Thus the activities of man, according to Setzer (1949), should be included in the soil-forming factors of tropical soils. With the exposure of the soil, leaching of the remaining bases is accelerated; the decomposition of the organic matter is rapid; and the physical condition of the soil deteriorates.

a. Patch Agriculture. One of the most common forms of agricultural development in the tropical areas is the so-called patch agriculture. The people learned from experience that by removing the forest by either clean cutting or burning they could produce several good crops. As crop yields deteriorated rapidly and became unprofitable, a new area was cleared and the old area was allowed to reforest. The basic concept was that the clear cutting or burning of the forest would cause a release of nutrients in the soil owing to the rapid decomposition of the humus. Soil exhaustion set in after this supply of readily available nutrients had been utilized by the plants or had been leached from the soil. Reforestation would rejuvenate the soil so that the process could in time be repeated. Rawitscher (1946), studying the exhaustion of tropical soils, concluded that deforestation leads to increased leaching and removal of essential bases, thus leading to the reduced crop yields.

The depletion of soil nutrients was not the only cause for lower crop production. The exposure of the soil caused the soil structure to deteriorate by the development of the Laterite crust. Humbert (1949) states that the main causes of soil exhaustion under this system of agriculture are as follows: (a) clear cutting in the forest; (b) fires; and (c) shifting cultivation practice in the forest. He states that it takes fifty years for the laterite crust to form after the removal of the forest. Chevalier (1949) has observed that with the removal of the forest, the laterite clays quickly become senile with the development of iron concretions and iron-oxide pans below the surface. The crust eventually appears at the surface, and the area becomes barren and unfit for the growth of plants. It takes trees forty years to restore productivity of the barren areas (bovals). Chevalier has found that laterite crust forms rapidly in New Guinea. Aubert (1950) considers crust formation as being a slower process, and according to his estimates it takes sixty years for the crust to form. Aubert (1949), Aubreville (1947, 1948), and Chevalier (1948) attribute the loss of productivity to the formation of the laterite crust due to its poor physical condition. Sherman *et al.* (1953) have found

that the crust has produced a poor physical condition, but there has been a loss of cation exchange capacity which also contributes to the infertile condition of the soil.

On the other hand, many workers believe that the rapid exhaustion of the "patch agriculture" system is merely a loss of available nutrients. Gautier (1946) and Carle (1938) believe the exhaustion of tropical soils is due to the continuous cropping without the return of fertilizer elements either in chemical form or through conservation through crop rotation practices. Marel (1948b) has pointed out that when tropical soils are placed under cultivation, the organic matter decomposes rapidly and develops a humus low in nitrogen, the lack of nitrogen being responsible for the reduced crop growth. Sody (1951) recognizes that the problem is both physical and chemical. He states that the applications of chemical fertilizers to those soils in which the soil structure has deteriorated will be largely wasted, as productivity will not be restored. Humus is necessary for regeneration of the soils, and an application of peat and chemical fertilizers is considered necessary to restore the productivity of the soil.

The people who practice "patch agriculture" agree that reforestation restores the soil to productivity. Chevalier (1949) believes it takes forty years for the forest to restore the nutrient levels and for the destruction of the laterite crust. Edelman (1946) states that old soils are rejuvenated by showers of volcanic ash and irrigation.

In general the followers of the "patch agriculture" system do not believe that it is feasible or profitable to apply fertilizers to tropical soils. Pendleton (1949) considered fertilization to be impracticable. Demolon and Aubert (1952) found that the applications of fertilizers to tropical soils were less effective than similar applications to temperate soils. As a consequence, the system of soil management has developed on the basis of utilizing only the available nutrients naturally occurring in the soil. Edelman and Beukering (1948) sum up the situation by stating that the present economic system in most of the tropical regions cannot afford chemical fertilizers, but that the application of fertilizers would increase agricultural production and would result in an economic improvement of tropical regions.

The laterite crust is very susceptible to destruction by erosion. Its removal by erosion leads to the exposure of a new surface on which a new soil can form. The new surface usually is a weathered horizon which in general is rich in kaolin minerals. Aubreville (1947), Aubert (1949), Aubert *et al.* (1948), Scaetta (1938), Henin (1949) and Sherman *et al.* (1949a) describe the destruction of the laterite crusts by erosion. The friable layer below the hardened iron oxide is extremely

susceptible to erosion, thus undermining the crust and causing its collapse. The erosion of the crust does not always lead to the exposure of a new soil surface, as in many cases the parent rock is exposed. In general, it is desirable to recommend practices which will prevent the crust from forming. Sherman *et al.* (1953) and Sherman and Kanehiro (1953) recommend the use of cover crops and mulches to prevent the dehydration of the soil which is necessary for the formation of the crust. Similar recommendations have been made by Gautier (1946). Chevalier (1949) states that the formation of the crust can be checked by providing cover or by the addition of basic rocks which have been pulverized.

b. Paddy Culture. Rice and taro are grown in many of the tropical regions. The former is one of the main food crops for the Asiatic peoples. The latter is the important food crop of peoples of the Pacific Ocean area. Both crops are grown by paddy culture, which means that the soil is submerged under a regulated flow of water for the greater portion of the crop-growing period. The soil is water-logged, but the water is never really stagnant. The soils are called paddy soils because the cultural practices have played a dominant role in the properties of the soil.

A paddy soil has certain very definite characteristics. It necessarily must be situated in the lowlands along streams in order to have a source of water. However, terraced paddies are found on hill slopes where water is available. All paddies are at different levels to obtain the greatest use of water by running it from one paddy to the next. A paddy soil is cultivated in its submerged state. The soil must disperse easily to permit the surface soil to puddle. The dispersed condition of the soil prevents the loss of water by percolation. The paddy soils must be high in clay, and evidence to date indicates that the dominant mineral in the clay fraction is of the montmorin series. Another characteristic of all paddy soils is the high content of exchangeable magnesium. Aso (1909) pointed out that the calcium : magnesium ratio of good paddy soils was approximately one. The junior author has found a similar relationship in the Hawaiian paddy soils. A very high content of ferrous iron and manganous manganese has been found in the water and soil of the Hawaiian paddy soils (Sherman and Fujimoto, 1946).

The culture of paddy soils depends a great deal on the dissolved nutrients carried down in the drainage waters from higher elevations. Thus, the most deficient element in paddies is nitrogen. In most of the Orient, nitrogen is supplied in organic forms, whereas in American rice areas the nitrogen is supplied as ammonium sulfate.

c. Intensive Culture. The intensive soil management practiced in the Hawaiian Islands and in parts of the Dutch East Indies has produced

returns which indicate that tropical soils have greater productive potentialities than would be predicted by the productive capacity under the "patch agriculture" system. The high yields obtained by the Hawaiian sugar cane and pineapple growers have been attained through the scientific research. This has established cultural practices which approach the maximum use of all factors of plant growth (Clements, 1951). The productive capacity of the Hawaiian sugar cane and pineapple industry is based on an intensive use of chemical fertilizers, irrigation water, and disease control, insect control, and plant breeding methods seldom encountered in agriculture in any part of the world. This system is in direct contradiction to the statements often made by agriculturalists in other tropical areas, that the use of chemical fertilizers is too expensive and the return is too small to justify their use. The Hawaiian growers lead the world in sugar and pineapple yields, and the growers have prospered from their operations.

Both the sugar cane and pineapple growers of the Hawaiian Islands have developed production practices based on years of experimentation. The fertilizer program practiced by both the pineapple and sugar cane growers is based on tissue and soil analysis. The "Crop Log" developed by Clements (1951) is used extensively in the sugar industry. Under "Crop Log," the fertilization and irrigation practices are planned according to the plant needs, which are determined by an analysis of responsive tissue of the sugar plant. Under this type of management, sugar cane yields have been as high as 15 tons of sugar per acre per 22 months.

The soils work of the Hawaii Agricultural Experiment Station has shown that the most appropriate tropical soil management is determined by the dominant minerals of the clay fraction of the soil. Matsusaka and Sherman (1950) have shown that the lime requirement and liming practices are determined by the type of minerals present in the fine silt and clay fraction of the soil. Chu and Sherman (1952) have shown a similar relationship for the phosphate fertilizers. The use of cover crops and mulches to prevent dehydration of certain hydrated oxides in order to maintain a productive soil has been described by Sherman and Kanehiro (1953). The application of fertilizer elements to mulches around the coffee tree, for example, is a means of feeding nutrients to a plant without their being fixed by the clay fraction of the soil. It has been found possible to use tensiometers to determine when irrigations are necessary on kaolin-rich soils. The moisture tension curves of kaolin soils show that most of the available water is held by a force of one atmosphere of tension or less. All of the results of the intensive culture in the Hawaiian Islands show that tropical soils are productive when the management of these soils is based on a thorough knowledge of the

chemical and physical properties of the soil. These properties are derived from its mineral composition, and thus management must include practices adapted to the montmorin, kaolin, and hydrated sesquioxide minerals which are dominant in individual soils. The soils of the Low Humic Latosol derive good physical properties from their high kaolin mineral content. Likewise the plastic properties of the soils of the Gray Hydromorphic group are the result of the high content of montmorin minerals (Gill and Sherman, 1952). The rapid crust formation of the soils of the Humic Ferruginous group is the result of the dehydration of the hydrated iron-oxide minerals which are dominant in these soils (Sherman *et al.*, 1953). These findings not only indicate the importance of the type of mineral to tropical soil management but also indicate that type of soil mineral in a soil should be considered in soil classification.

V. Summary

Chemical weathering of minerals present in soils or in soil parent materials is viewed from the standpoint of its relation to the nature of soils as natural bodies and also from the standpoint of the capacity of minerals in soils to furnish nutrient elements for the growth of crops. These relationships have been examined for both temperate and tropical climatic conditions.

Chemical weathering is the change in mineralochemical composition of consolidated or unconsolidated rock which occurs within the influence of atmospheric and hydrospheric agencies. Physical weathering hastens chemical weathering by increase of specific surface. Hydrothermal and deuteric alterations of minerals produce changes which are similar to some of those produced by weathering. For convenience of discussion, chemical weathering may be subdivided into pedochemical weathering, occurring in the soil proper, and geochemical weathering occurring in the geologic column and forming soil parent material. The degree of chemical weathering and the processes of it remain the same, regardless of whether chemical weathering is classified into one or the other of these categories. In either case, chemical weathering of minerals largely determines the nature of colloidal minerals present in soils; if it is held that most of the chemical weathering occurs in the parent material, then the conclusion must be accepted that the mineralogy of soils and thus many important soil properties are determined to like extent by the parent materials of soils.

When a mixture of minerals deposited together in one rock formation is subjected to the agencies of chemical weathering, some minerals are weathered faster than others. A list of minerals according to their

relative stability to weathering is designated a "weathering sequence." Different weathering sequences have been worked out for minerals of heavy specific gravity, coarse-grained minerals, colloidal minerals, and combinations of these categories. Chemical weathering of soil minerals is considered mainly in terms of the colloidal products, and the sequence of colloidal minerals is therefore accorded the main emphasis. That sequence is represented by a type mineral of each stage of weathering as follows: (1) gypsum, (2) calcite, (3) hornblende, (4) biotite, (5) albite, (6) quartz, (7) muscovite, (8) vermiculite, (9) montmorillonite, (10) kaolinite, (11) gibbsite, (12) hematite, and (13) anatase. With each stage is associated a group of minerals having similar though not identical weathering stabilities. Indexes which have been employed for the representation of chemical weathering include several types of molar ratios, but a weathering mean based on the weighted average of the weathering stage of minerals present offers a sensitive measure of the degree of weathering of soil minerals, and it is particularly more sensitive in stages 4–9 than are molar ratios.

The reaction rates of chemical weathering are controlled by various intensity and capacity factors operating as a function of time, and different combinations of intensities, capacities, and times of weathering may produce a given degree or stage of weathering. Methods of measurement of the factors affecting rate of chemical weathering reactions include the analysis of soils in different geographic and catenary locations, with different specific surface of material, and in different degrees of proximity to the soil surface. A relationship of chemical weathering to soil groups is noted: namely, to the extent that the stage of chemical weathering of a material is correlated with climate and that soil groups are correlated with climate, there tends to be an association of colloidal mineral weathering products with the soil groups (proposition A). However, to the extent that chemical weathering has occurred over longer time or with greater intensity factors, the minerals will be more weathered than is expected for the soil formation (corollary IA); and to the extent that soil formation progresses faster than chemical weathering reactions, there will be different soil groups with the same minerals (corollary IIA). Similarly, there is an association of chemical weathering products with marked changes in relief and corresponding soil groups (proposition B), but corollary conditions for exceptions occur with this proposition also. The weathering sequence is recapitulated in the particle-size function, that is, the minimum size of a mineral particle that can exist in a given environment is a function of the stability of the mineral. Owing to greater leaching and temperature near the soil surface there tends to be a greater degree of weathering near the soil surface

than deeper (the depth function), with the result that the weathering stage advances with proximity to the surface. The depth function is generally apparent in the geochemical profile, extending down to the unweathered rock, but often is not apparent within the root zone.

The capacity factors of weathering include the specific surface of the material and the specific weatherability of the minerals. The intensity factors of weathering may be classified as temperature, water and leaching, acidity, biotic, and oxidation-reduction factors.

Chemical weathering together with some hydrothermal and deuteric alterations is responsible for the frequency distribution of colloidal minerals which occur in soils. It is clear that much of the chemical weathering of minerals now existing in soils took place during geologic time, including cycles of erosion and sedimentation, and that much of it took place as the material stood in the geologic column prior to its exposure to soil formation. Some of it has taken place in the soil itself during the process of soil formation. Examples of soil mineral occurrence in each of the stability stages have been reported in the literature reviewed. The general conclusion can be drawn that there is a systematic and continuous advance in the stage of weathering of soil material with time and intensity factors of chemical weathering. For this reason, kaolin, gibbsite, and allophane, hematite and geothite, and anatase and ilmenite are much more abundant in the warmer regions, whereas the earlier stages of weathering are more in evidence in the temperate and cool regions. But old geologic formations in temperate regions invariably show more minerals of the advanced stages. When the colloidal mineral composition of a soil is plotted against the mineral weathering stages, a distribution curve results. As the degree of weathering increases this distribution curve shifts functionally.

It is found that the inherent fertility of soils is related to their mineral content. As the weathering stage advances, soils gradually change, first toward increased productivity and finally to extremely low productivity. The release of the major and minor elements can be correlated with mineral composition of the soil. In the backward areas, agriculture has been directed toward maximum use of the native mineral source of nutrients by such systems as patch agriculture and paddy culture. Even in areas of intensive agriculture, it is clear that the addition of ground rocks (such as ground limestone) and minerals to soils is a reversal of the weathering scheme, with extremely beneficial effects on crop productivity.

Acknowledgments

Our warm gratitude is extended to the following scientists who generously helped with the labor of this review by supplying abstracts of their own and their associates' work on the weathering of minerals: H. W. van der Marel and F. A. van Baren (Netherlands and East Indies), E. R. Graham and R. H. Bray (United States), J. Shearer (Australia), H. C. Aslyng, F. Steenbjerg, and A. Unmack (Denmark), I. Stephen (England), G. Semb and R. Selmer-Olsen (Norway), L. Wiklander (Sweden), Toshio Sudo (Japan), S. Henin and S. Caillere (France), and H. Deuel (Switzerland).

In addition the authors have had the benefit of valuable council with Dr. Guy Smith of the United States Department of Agriculture and Dr. F. D. Hole of the University of Wisconsin.

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The Changing Pattern of Agronomy and Horticulture in Canada

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CONTENTS

I. Introduction

1. *Agriculture in the National Economy*

During the last forty years, between 1911 and 1951, Canada's national economy has expanded greatly. The population of Canada has approximately doubled and the total annual external trade has increased more than tenfold in the last four decades. The effect of the two World Wars has been enormous. During and immediately after the 1914–1918 war Canada's total external trade more than trebled, increasing from \$769,450,000 in 1911 to \$2,450,000,000 in 1921. Following World War II Canada's external trade rose in 1951 to \$8,048,000,000.

As shown in the last four Census Reports, profound changes have occurred, also, in Canadian agriculture.

TABLE I

Gross Value of Total Production, and of Agricultural, Manufacturing, Pulp and Paper, and Mineral Production in Canada [a]

		Gross value of production, in thousands of dollars				
Year	Population	Total	Agricultural	Manufacturing	Pulp and paper	Mineral
1921	8,788,483	4,177,836	1,386,126	2,488,987	116,891	171,923
1931	10,374,196	4,132,112	836,441	2,555,126	62,769	230,435
1941	11,420,084	8,744,662	1,432,601	6,076,308	163,412	560,241
1951[b]	14,009,429	21,241,000	3,488,389	13,817,524[c]	954,138[c]	1,228,005

[a] Data from Canada Bureau of Statistics.
[b] Estimated.
[c] 1950 figures.

Although the value of agriculture has expanded in 1951 to nearly three times that of 1921, the relative value of manufacturing and of certain other industries has risen at a much faster rate. This situation was well expressed by Booth (1951):

"In 1905 . . . agriculture was relatively more important than it is today; nearly two-thirds of the population were classified as rural and about 40% of the gainfully employed were engaged in farming . . . Today the rural population is in the minority and of the working force less than a quarter is engaged in agriculture. This is the inevitable development of a young country richly endowed with a variety of natural resources. Agriculture is still one of our most important industries, however, and in some respects more important today than at the beginning of the century."

The gross value of agricultural production in 1921, as shown in Table I, was about one-third of the total gross value of production in Canada, whereas in 1951 it was only one-sixth. It should be remarked, however, that there is some duplication in the values shown in this table for manufacturing, as these include the value of unprocessed or partly processed materials obtained from agriculture and other basic industries. Of course, inflation of currency accounts for part of the increased dollar values.

The value of the production per farm in Canada between 1901 and 1950 has increased over 100 per cent. Both scientific research and mechanization have contributed in bringing about increased farm output.

2. *Agronomic Trends*

The area devoted to field crops in Canada has more than doubled in forty years, rising from 30,556,000 acres in 1911 to 64,049,000 in 1951. The values of field crops have increased over fivefold during the period, from $384,514,000 in 1911 to an estimated $1,977,000,000 in 1951. Wheat is the most outstanding Canadian crop, with oats in second place, and hay, barley, potatoes, and tobacco following in that order. Of these six field crops tobacco, barley, and wheat have increased most in relative production and values between 1911 and 1951. Mixed grains, chiefly oats and barley seeded in 50:50 mixture, is an important crop in Quebec and Ontario.

Pasture acreage in Canada, both improved and unimproved, has steadily increased during the past four decades. Of the total of 10,005,000 acres improved pasture in 1951, 6,523,364 acres, or almost two-thirds, was in the six eastern provinces; whereas of the 54,414,000 acres of unimproved pasture in 1951, 46,788,600 acres, or about four-fifths, was in the three Prairie Provinces and British Columbia. The improvement and better utilization of pastures is of major concern to Canada's live-

stock growers, forage plant breeders, and soils and field husbandry specialists.

The various sections of this article have been prepared by different authors assisted by other specialists. There are many points of similar interest in the diverse fields of agronomy and horticulture, such as the effects of soils, climates, diseases, insects, and economic conditions. For specific information on the articles in various fields the reader is advised to refer to the Table of Contents.

Section II, on Cereals, describing the trends in cereal production, gives information on the progress of cereal breeding and the successive introduction of new varieties of cereals designed to meet specific needs throughout Canada. Section III, Field Husbandry, Soils, and Agricultural Engineering, discusses trends in methods of investigation and practices followed relating to soils, fertilizers, agricultural machinery, cropping, irrigation, pasture, soil surveys, and weed control since 1918. The article on Forage Crops (Section IV) shows the regional importance and trends of forage crop production in Canada, as well as the accomplishments in breeding new varieties.

Section V on Horticulture outlines the development of commercial horticulture in this country since 1918. Trends in horticultural practices and in the breeding of fruit and vegetable varieties are described. Short accounts are given of the development of greenhouse crops and of vegetable growing on organic soils in Canada. The remarkable expansion during the last forty years of tobacco production in Canada, particularly of the flue-cured type, is briefly discussed in Section VI, as well as the successes which have been obtained in breeding new varieties of tobacco.

II. Cereals *

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In this brief section an attempt is made to evaluate some of the effects of cereal breeding progress on trends of cereal production in Canada. A new variety with improved characteristics becomes immediately an economic factor in that it may reduce the cost of production or make production possible in areas or under conditions otherwise quite unsatisfactory. The story of MARQUIS wheat and its effect on agriculture in the Prairie Provinces is a case in point. The same is true of the rust-resistant wheats in Manitoba and eastern Saskatchewan. Early varieties

* Contribution No. 168 from the Cereal Division, Experimental Farms Service, Canada Department of Agriculture, Ottawa, Canada.

of barley have been a contributing factor in the replacement of wheat by barley in some areas, particularly in northern Alberta. These examples are pointed out in some detail, and others are dealt with as space permits.

1. Wheat

Since wheat is the predominating cereal in Canada, it is obvious that all factors affecting wheat production must have an indirect effect on the production of other cereals. The figures † below show the acreages, in thousands of acres, of cereal crops in Canada in the year 1951.

Wheat	25,731	(spring and winter)
Oats	12,065	
Barley	8,030	
Rye	1,127	
Flax (for seed)	1,112	
Mixed grain	1,806	

Throughout the period being considered, 1910–1950, wheat has generally been the most profitable cereal crop. The average gross values of an acre of wheat expressed as acres of oats, barley, and flaxseed for the Prairie Provinces are:

Oats	1.37
Barley	1.29
Flax	1.21

showing a consistent margin in favor of wheat production.

The acreage figures for wheat in averages for five-year periods are given in Table II. The figures in all columns, except those for Ontario, are for spring and winter wheat combined. In the other columns the proportion of winter wheat is so small that the values given can be regarded as representing spring wheat.

The trend in spring wheat in the eastern provinces has been steadily downward throughout the entire period. In these areas spring wheat is grown almost entirely for chicken feed or for grist at local mills. The competition from western feed grain and the decreasing production of flour in small mills for local consumption are factors which have contributed to the downward trend.

In the Prairie Provinces there was an almost continuous and rapid increase in the wheat acreage from 1908 with 5,624,000 acres to 1922 with 22,181,000 acres. In order to understand this increase together

† Crop statistics taken from Handbook of Agricultural Statistics, Part I—Field Crops, and Quarterly Bulletin of Agricultural Statistics, Dominion Bureau of Statistics, Ottawa, Canada.

with the corresponding increase in agricultural development all across the prairies, it is necessary to go farther back in the history of wheat production. Buller (1919) in *Essays on Wheat* gives an excellent account of the efforts of the Selkirk settlers to grow wheat on the banks of the Red River approximately where the city of Winnipeg is now situated. The first party arrived at the Red River in 1812, and having brought cereals with them from Great Britain, immediately began preparing the land for crops. They sowed winter wheat in the fall of 1812 and some spring wheat, barley, and peas in the spring of 1813. There was great disappointment when the wheat harvest proved to be a total failure. From our present knowledge of the climate of Manitoba and the types of varieties of cereals that the settlers were most likely to have brought with them, the results obtained are not surprising. Repeated efforts by the early settlers to produce wheat from seed from Great Britain were almost a total failure. Even when the crop appeared to be a success it was destroyed by storms, locusts, or grasshoppers.

It is noteworthy that the first successful crop of wheat produced by the Selkirk settlers was in 1820; this crop came from seed that they imported at great expense and difficulty from Prairie Du Chien in the state of Wisconsin. It is not known if the wheat imported was a named variety, but it is most likely that it was brought to the United States by European settlers. It appears to have been better suited than the English varieties to Manitoba conditions, as Buller states that in spite of frequent crop failures the Red River settlers did not again lack wheat for seed until 1868, when the crops were completely destroyed by grasshoppers.

There is no clear record of the source of seed of wheat crops grown by the Selkirk settlers following the disaster of 1868, but it seems likely that they obtained further supplies from the United States. It is stated by Clark (1936) that the first successful crop of RED FIFE wheat in the United States was obtained by a Wisconsin farmer in 1860. This variety had come to the United States from Ontario. It came to Ontario from Great Britain but seems to have come originally from the Ukraine.

The wheat being grown in the Prairie Provinces in 1908 was very largely of the RED FIFE variety, although Dr. William Saunders and Dr. Charles Saunders of the Experimental Farms Service had been making prodigious efforts to obtain an earlier high-yielding variety. They had introduced such early varieties as EARLY RED FIFE, PRELUDE, LADOGA, and PRESTON. LADOGA was unsatisfactory in quality, and the others had agronomic defects. From what we now know of weather conditions in the prairies following 1908 it is quite certain that RED FIFE wheat would not have supported a rapidly expanding agriculture. It would most

certainly in many seasons have succumbed to fall frosts and been severely damaged by stem rust, with the result that farmers would have been forced into the production of feed grains or varieties of wheat of inferior quality.

The distribution of MARQUIS wheat, which took place in 1909, marked the beginning of a new era in Canadian wheat production. It was from a week to ten days earlier than RED FIFE and gave excellent yields. It spread very rapidly and in a few years was practically the only variety grown in the Prairie Provinces. It was undoubtedly the desirable characteristics of this variety that made possible the great expansion in acreage from 1910 to 1921. If the farmers had been restricted to the use of RED FIFE it is certain that there would have been very little wheat production outside of the southern areas of the prairies, where the danger from fall frosts is a minimum.

Another factor affecting wheat production in the Prairie Provinces, and Manitoba and Saskatchewan in particular, was the occurrence of epidemics of stem rust (*Puccinia graminis* Pers.). The first disastrous outbreak was in 1916, when it was estimated that the damage resulted in a reduction of 100,000,000 bushels in the wheat crop. In the period from 1916 to 1938, Craigie (1945) shows that there were five heavy epidemics, six medium epidemics, and twelve light ones. Calculations made by Greaney (1936) show that for Manitoba and Saskatchewan the average annual loss between 1925 and 1935 was approximately 35,000,000 bushels.

During the first heavy epidemics of stem rust it was noted that durum wheat seemed to be more resistant than the common wheats, and many farmers in Manitoba switched to the production of durums. For this reason the proportion of the acreage of durums in Manitoba in 1928 reached 56 per cent. The differential effect was due, apparently, to the occurrence of races of stem rust to which the common wheats were susceptible and the durums resistant. With the introduction of resistant varieties of both common and durum wheat, the proportion of durums was reduced and at the present time the latter occupy only about 10 per cent of the wheat acreage in Manitoba.

The first rust-resistant common wheat variety distributed was THATCHER. The distribution took place in 1936, and in about three years almost the whole of the crop in Manitoba was of this variety. Shortly after 1936 other rust-resistant varieties appeared, such as RENOWN, APEX, REGENT, and REDMAN. Table IV shows the percentage of the acreage occupied by these varieties in 1941 and 1951. In Manitoba the wheat acreage at present is almost entirely of rust-resistant varieties. In Saskatchewan the resistant varieties make up 94 per cent and in Alberta

88 per cent of the acreage. This reflects not only the additional value to the farmer of freedom from rust damage but also the improvement in agronomic characteristics brought about by the plant breeders in these new varieties.

In Alberta, for example, damage from stem rust has always been quite small, and the fact that the farmers have switched from susceptible varieties such as MARQUIS, RED BOBS, and GARNET, to THATCHER, RESCUE, REDMAN, and SAUNDERS is a reflection of advantages other than resistance to rust obtained through the use of these varieties.

For convenient reference Table III gives a chronological record of the distribution of wheat varieties in Canada.

In Manitoba it is easily proved by comparing yields in plot tests where MARQUIS is grown that the average yields have been noticeably increased by the use of resistant varieties. Actual averages by five-year periods are also indicative. These are given below for the eight five-year periods being considered here:

1910–1914	17.7
1915–1919	16.6
1920–1924	14.7
1925–1929	17.3
1930–1934	14.5
1935–1939	14.0
1940–1944	22.2
1945–1949	19.8

The effect of the rust-resistant varieties is shown in the last two five-year periods. Calculations of this sort are of course inconclusive because of the confounding effect of seasonal conditions. Even in rust epidemic years such as 1916, the actual production figures in bushels do not give a true measure of the loss to the farmers, as most of the wheat produced is of very low grade.

A recent development in the rust situation is the occurrence of new races of stem rust to which varieties such as THATCHER and REDMAN are susceptible. Race 15B, which is of this type, occurred over a considerable area in the Prairie Provinces in 1951 and was in epidemic proportions in 1952, although it came too late to cause noticeable damage to common wheats. The durum varieties being grown are more susceptible to this race than are the common wheats, and some late crops in Manitoba were severely damaged. It is of interest that this situation is directly the reverse of that when heavy rust epidemics first began to occur. The indications at the present time are that durum wheats will decrease rapidly until a variety can be produced that is resistant to race 15B.

Plant breeders began working on the development of more resistant

varieties as soon as race 15B was discovered in 1938, and as a result several resistant strains of common wheat have been produced which are now being tested and increased for distribution. It is expected that they will be ready for production on a commercial scale in time to prevent the new races of stem rust from having any definite effect on trends in wheat production.

As already pointed out, the distribution of MARQUIS wheat made wheat production possible over a much greater area in the Prairie Provinces. The introduction of still earlier wheats, such as RED BOBS, GARNET, and SAUNDERS, extended successful wheat production farther north. In the Peace River area of Alberta there is definite need for an early variety and also in the area around Edmonton and extending southward along the foothills of the Rocky Mountains. GARNET and RED BOBS filled the

TABLE II

Acreages of Wheat in the Chief Producing Areas of Canada by 5-Year Periods
Data in Thousands of Acres

Period	Maritimes	Quebec	Spring wheat Ontario	Winter wheat Ontario	Prairie Provinces	British Columbia	Canada
1910–14	57	61	116	759	9,448	12	9,694
1915–19	81	206	207	677	15,145	27	15,666
1920–24	70	138	151	727	20,438	46	20,843
1925–29	47	62	113	738	22,069	55	22,346
1930–34	39	54	98	547	24,883	61	25,135
1935–39	37	51	92	652	24,698	66	24,944
1940–44	16	29	46	673	21,616	86	21,793
1945–49	9	23	43	719	23,800	122	23,997

TABLE III

Chronological Record of the Distribution of Spring Wheat Varieties in Canada to 1950

Before 1910	BISHOP, EARLY RED FIFE, HURON, MARQUIS, PRELUDE, PIONEER, PRESTON, RED FIFE
1910–14	
1915–19	RUBY
1920–24	KOTA, QUALITY, RENFREW
1925–29	CERES, GARNET, RED BOBS, REWARD
1930–34	RELIANCE
1935–39	APEX, CANUS, CORONATION, REGENT, RENOWN, THATCHER
1940–44	
1945–49	CASCADE, REDMAN, RESCUE, SAUNDERS
1950	ACADIA, LEE

need for a number of years, but they are now being replaced by THATCHER and SAUNDERS. The replacement is due in part to the degrading of RED BOBS and GARNET because of deficiencies in quality for making bread.

TABLE IV [a]

Distribution of Wheat Varieties in Percentage of the Total Acreage for the Prairie Provinces 1941 and 1951

Variety	Manitoba 1941	Manitoba 1951	Saskatchewan 1941	Saskatchewan 1951	Alberta 1941	Alberta 1951	Prairie Provinces 1941	Prairie Provinces 1951
THATCHER	61.8	28.4	63.8	70.6	6.7	53.8	45.2	59.9
RESCUE	—	—	—	13.1	—	5.2	—	8.9
REDMAN	—	39.4	—	3.5	—	2.7	—	7.7
MARQUIS	0.1	—	17.1	3.1	37.1	9.2	21.9	4.7
SAUNDERS	—	0.2	—	0.6	—	12.4	—	4.3
REGENT	7.8	18.0	3.0	1.2	0.3	1.3	2.6	3.3
DURUM VARIETIES	6.2	10.8	0.9	3.2	—	0.2	1.1	3.2
GARNET	—	—	0.1	0.6	2.5	8.4	0.9	3.0
RED BOBS	0.1	—	1.4	0.3	47.4	4.1	16.1	1.5
APEX	1.0	0.1	8.3	1.7	0.2	0.2	5.0	1.0
REWARD	0.5	—	0.7	—	1.4	—	0.9	—
RELIANCE	—	—	0.1	—	0.1	—	0.1	—
CANUS	—	—	—	—	2.3	—	0.7	—
WINTER WHEAT	—	—	—	0.1	1.0	0.9	0.3	0.4
LEMHI (soft white)	—	—	—	0.1	—	0.6	—	0.3
RENOWN	22.1	—	4.0	—	0.5	—	4.7	—
OTHERS	0.3	3.1	0.6	1.9	0.5	1.0	0.5	1.8

[a] Data in Tables III, VI, IX, and XII, by Courtesy of North-west Line Elevators, Winnipeg, Manitoba, Canada.

2. *Oats*

Table V gives the average acreages of oats in Canada in the chief producing areas, by five-year periods, from 1910 to 1949. The trend in eastern Canada shows rather small changes in the Maritimes and Quebec, but there is a fairly definite downward trend in Ontario. This trend in Ontario is only partially made up by a corresponding increase in mixed grains. In the Prairie Provinces there has been a considerable increase, but most of this increase took place in the period from 1910 to 1920.

It does not seem possible to come to any definite conclusions with respect to changes in the oat acreage in the Prairie Provinces being due to any specific factors. In the period 1910–1920 there was of course a general increase in cereal production. If the five-year period 1910–1914 is compared with the period 1920–1924, wheat acreage increased 116 per

cent and oat acreage 89 per cent. The determining factors in furthering cereal production were probably those factors affecting wheat; hence, oats increased correspondingly because of the increased demand for feed and because in many areas it fitted in well as a second crop in the rotation.

It is of some interest to examine the ratio of returns per acre for wheat and oats in the Prairie Provinces over the years for which data are available. A detailed analysis would be required to bring out any definite trends. We observe, however, from the values given in Table V, that the period 1925–1929 represents a reduction in comparison with the two previous five-year periods, and at the same time that there is a corresponding increase in the wheat: oats ratio which may have had an effect in causing farmers to switch oat acreage to wheat or barley.

There does not seem to have been any pronounced effect of new and improved varieties on the acreage of oats. Table VI shows the important varieties of oats grown in Canada since 1910 and the date of their distribution. It is of interest to study this table in relation to the data of Table VII, giving the percentage distribution of oat varieties in 1951. The original oat acreage consisted almost entirely of BANNER and VICTORY. These varieties were almost the only ones grown in the period from 1910 to 1936. A few early varieties such as 60 DAY and KHERSON were tried by farmers but generally discarded on account of low yields and low weight per bushel. The varieties LEGACY and CARTIER were of little importance in this period, the former being adapted in only a small area, and the latter having a distribution almost entirely confined to Quebec. In 1936, VANGUARD, the first variety having resistance to stem rust, made its appearance and was followed by several other resistant varieties in the years from then on to the present. The rust-resistant varieties in

TABLE V

Acreage of Oats in the Chief Producing Areas of Canada by 5-Year Periods, and Wheat: Oats Returns per Acre Ratio. Data in Thousands of Acres

Period	Maritimes	Quebec	Ontario	Prairie Provinces	British Columbia	Canada	Wheat: Oats returns
1910–14	481	1,352	2,823	5,050	46	9,752	1.15
1915–19	543	1,608	2,674	8,241	55	13,121	1.38
1920–24	577	2,097	2,974	9,537	59	15,244	1.44
1925–29	489	1,813	2,671	7,772	85	12,830	1.57
1930–34	463	1,738	2,375	8,632	93	13,301	1.36
1935–39	457	1,677	2,305	8,695	111	13,245	1.47
1940–44	402	1,684	1,872	9,572	84	13,614	1.21
1945–49	377	1,481	1,673	8,409	81	12,021	1.38

Table VI are shown in italics. These varieties now dominate the acreage of the eastern Provinces and Manitoba and the eastern half of Saskatchewan, and have undoubtedly made very important contributions to average yields. The increases in yield owing to the rust-resistant varieties can be estimated by comparing yields in test plots. Estimates made in this way demonstrate that the increases have been appreciable. They do not show in average production figures, because these figures would undoubtedly have been reduced if the rust-resistant varieties had not been available.

TABLE VI

Chronological Record of the Distribution of Oat Varieties in Canada to 1950

Period	Varieties							
Before 1910	BANNER,	VICTORY,						
1910–14								
1915–19								
1920–24	LEGACY,							
1925–29								
1930–34	CARTIER,							
1935–39	EAGLE,	*Erban,*	MABEL,	*Vanguard,*				
1940–44	*Ajax,*	BRIGHTON,	DASIX,	*Exeter,*	*Roxton,*	VALOR,		
1945–49	*Abegweit,*	BAMBU,	*Beacon,*	*Beaver,*	*Clinton,*	*Fortune,*	*Garry,*	LARAIN,
1950	*Lanark,*							

TABLE VII

Distribution of Oat Varieties in Percentage of Total Acreage in the Prairie Provinces—1951

Variety	Manitoba	Saskatchewan	Alberta	Prairie Provinces
VICTORY	3.7	33.7	58.0	37.7
AJAX	32.0	26.9	7.4	21.3
EXETER	33.6	14.6	0.8	12.6
BANNER	1.1	10.0	10.5	9.0
VANGUARD	22.1	4.6	1.9	5.9
GOPHER	2.2	4.8	0.4	3.1
EAGLE	—	0.2	9.2	3.0
LARAIN	0.2	0.4	8.3	2.9
FORTUNE	0.4	1.9	0.2	1.2
GARRY	1.9	0.5	0.4	0.7
BEAVER	0.2	—	1.0	0.3
OTHERS	2.6	2.4	1.9	2.3

3. *Barley*

Barley acreage figures for the period 1910–1949 are given in Table VIII. The trend in the eastern provinces during the last fifteen years has been distinctly downward and in this respect parallels the trend with oats. Since both are feed grains, this parallel is to some extent to be expected, in that they are both affected by the cheapness with which feed grains can be brought from the Prairie Provinces. When it is cheaper to freight feed grain from the west than it is to grow it, there is a tendency for eastern farmers to put more of their land into forage crops or cash crops. Barley production in the eastern provinces must, however, be considered in relation to the production of mixed grain, the acreages for which are given in Table XIV. In Ontario, for example, the increase in acreage of mixed grain from the first to the last five-year period is 633,000 acres. If we assume that one-half of this is barley, the acreage for 1945–1949 can be increased by 316,000 acres, making a total of 512,000. There is actually, therefore, an increase in total barley production.

With respect to straight barley production in Ontario and Quebec, there is need for more suitable varieties if the downward trend is not to continue. In spite of reasonably adequate rainfall in nearly all seasons, the average yields are not as high as might be expected. This seems to be due to sensitivity of the barley crop to lack of fertility in the soil, weakness of straw resulting in lodged crops, and susceptibility to disease. With respect to the latter, recent observations indicate that there is a good deal more loss from root rots than had formerly been thought.

In the west there has been a large increase in the acreage of barley during the past fifteen years. The figures in thousands of acres given below for the 1935 and 1951 barley acreages in Manitoba, Saskatchewan, and Alberta, are of particular interest.

	Manitoba	Saskatchewan	Alberta
1935	1,121	1,146	920
1951	2,040	2,561	3,011
% increase	82	123	227

The greatest increase has taken place in Alberta, which has now become our leading barley-producing province. This is apparently the result of an increasing demand for feed grain, and dissatisfaction with the performance of wheat, particularly in the northern areas. The early varieties of barley, particularly NEWAL and OLLI, have been important factors in inducing farmers in the northern sections of Alberta to change from wheat to barley production. It can be observed from Table X that

the two leading varieties in 1951 are NEWAL, which occupied 23 per cent of the Alberta acreage, and OLLI, which occupied 21 per cent of the acreage.

It is of interest at this point to compare the relative increases in acreage of wheat, oats, and barley in the Prairie Provinces from 1910 to 1951. The figures in thousands of acres are given below:

	1910	1951	1951:1910
Barley	667	7,612	11.4
Wheat	7,867	24,574	3.1
Oats	3,881	7,954	2.0

Since there has been a more or less steady increase in barley acreages, it seems to represent a growing realization by the farmers of the profits to be made from the barley crop, the suitability of the crop in the rotations system, an increasing demand for barley as a feed, and improved varieties. When all barley varieties were rough-awned, farmers generally disliked handling the crop. The smooth-awned varieties have tended to overcome this difficulty, and in addition the introduction of the combine harvester has minimized handling discomfort.

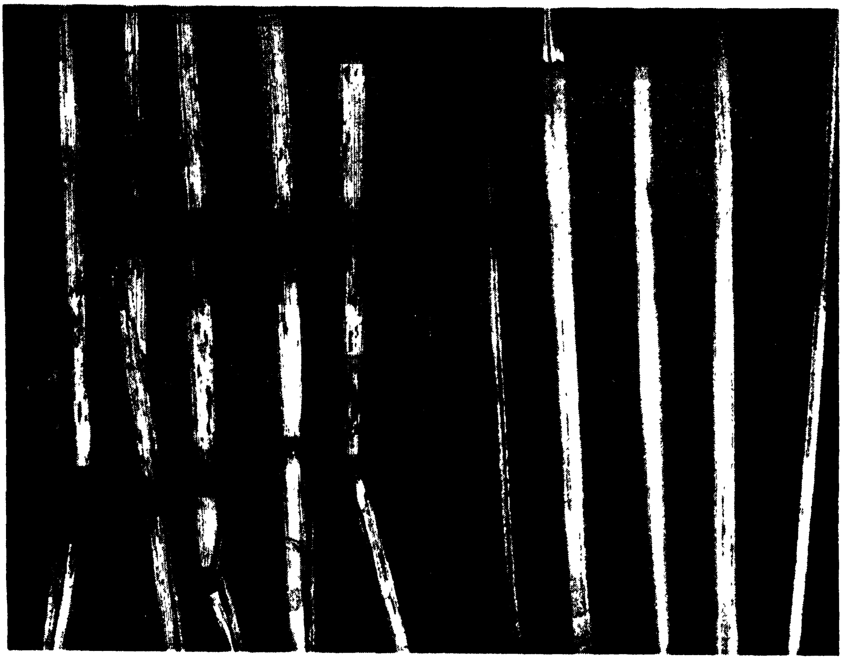

FIG. 1. Left, stems of a susceptible variety of barley showing pustules of stem rust. Right, stems of a resistant variety of barley grown under comparable conditions.

The varieties of barley that have been made available to farmers in the forty-year period under discussion are shown in Table IX. This table should be examined in conjunction with Table X, showing the distribution of the varieties in the Prairie Provinces for 1951. O.A.C. 21 has been a popular variety from the beginning and was dominant in the Prairie Provinces until the introduction of MONTCALM in 1945, which gives somewhat higher yields than O.A.C. 21 and has a semismooth awn. The first rust-resistant variety to be distributed was PEATLAND, but this variety did not become popular owing to its lack of general adaptability. The next variety having resistance to stem rust was VANTAGE, which is now gaining in popularity.

The most striking fact about barley production in Canada is the continued increase in production over a period of forty years as compared to other cereal grains. This is accounted for in part by the introduction

TABLE VIII

Acreage of Barley in the Chief Producing Areas of Canada by 5-Year Periods, and Wheat:Barley Returns per Acre Ratio. Data in Thousands of Acres

Period	Maritimes	Quebec	Ontario	Prairie Provinces	British Columbia	Canada	Wheat:barley returns
1910–14	12	93	496	895	3	1499	1.20
1915–19	17	150	473	1697	6	2343	1.23
1920–24	21	158	454	2186	8	2827	1.25
1925–29	21	131	527	3609	8	4296	1.52
1930–34	24	126	492	3423	10	4075	1.47
1935–39	30	162	533	3553	14	4292	1.24
1940–44	43	147	365	5886	20	6461	1.22
1945–49	31	137	256	6278	15	6717	1.22

TABLE IX

Chronological Record of the Distribution of Barley Varieties in Canada, to 1950

Period	Varieties				
Before 1910	CHARLOTTETOWN 80				
1910–14	HANNCHEN,	O.A.C. 21			
1915–19					
1920–24	MENSURY,	TREBI			
1925–29	VELVET				
1930–34	COLSESS,	PEATLAND,	REGAL,	WIS. 38	
1935–39	BYNG,	GARTONS,	NEWAL,	OLLI,	PLUSH, REX
1940–44	GALORE,	PROSPECT,	SANALTA,	TITAN,	WARRIOR
1945–49	BARBOFF,	COMPANA,	MONTCALM,	VANTAGE	
1950	HARLAN,	VELVON II			

of early varieties enabling farmers to switch from wheat to barley production, especially in the northern areas, and thereby escape the danger of fall frosts. Other factors have, of course, been equally important, such as the growing need for barley as a feed, a larger market for malting barley with the accompanying premiums for barley of good quality, and the need for an early crop in the rotation for late sowing and for the control of weeds such as wild oats.

TABLE X

Distribution of Barley Varieties in Percentage of Total Acreage in the Prairie Provinces in 1951

Variety	Manitoba	Saskatchewan	Alberta	Prairie Provinces
MONTCALM	56.3	22.6	14.5	24.2
O.A.C. 21	19.7	12.2	11.3	12.9
HANNCHEN	—	17.1	1.2	9.8
NEWAL	0.1	1.2	22.6	8.0
PLUSH	5.5	12.6	0.7	7.9
OLLI	0.7	0.8	21.1	7.3
COMPANA	—	3.4	14.2	6.5
TITAN	0.4	9.8	1.7	6.0
TREBI	0.9	3.9	6.3	4.3
PROSPECT	0.5	6.7	—	3.7
REX	—	3.1	1.1	2.0
SANALTA	3.7	0.7	1.7	1.4
GARTONS	7.0	0.1	—	1.0
VANTAGE	2.6	0.7	0.9	1.0
Others	2.6	5.1	2.7	4.0

4. *Flaxseed*

Flaxseed production in thousands of acres in the chief producing areas of Canada is shown in Table XI by five-year averages for the period from 1910 to 1949. In the first place we note an almost gradual reduction in the five-year averages for all of Canada from the 1910–14 period to the 1935–39 period. This is influenced largely by the trend in Saskatchewan, which throughout the period denoted was the dominant producing province. In the early years of flaxseed production in the Prairie Provinces, farmers found that flax was an excellent crop for newly broken land, and this accounts in part for its popularity in those times. In Saskatchewan in particular the commonly grown varieties such as PRIMOST and NOVELTY matured in good time when sown on breaking. As less new land became available, flax was grown on summer fallow, and a combination of drought years and years in which early fall frosts dam-

aged the crop brought about a gradual decrease in the popularity of the crop.

Porteous (1952) has given an excellent analysis of the causes of the trends in flaxseed production in the Prairie Provinces in the period from 1910 to 1951. He has indicated the existence of cyclic trends associated with the ratio of the gross value per acre of flax to the gross value per acre of wheat. This has affected flax production with reasonable equality in all areas, but there have been periods when it affected Saskatchewan flax production more adversely than Manitoba production. Manitoba production increased in the 1920–1924 period and then dropped with Saskatchewan until the period 1935–1939. Since that time it has increased fairly steadily, however, and in 1948 the acreage exceeded that of Saskatchewan by 360,000 acres. It has since remained in the lead.

The factors favoring production in Manitoba as compared to Saskatchewan are better moisture conditions, greater freedom from insect damage, and a lower average fall frost hazard. These advantages did not have much effect on flax production in Manitoba until the introduction of chemical weed control, as the moisture conditions in Manitoba had always favored weed growth in the flax crop. A further factor which has not previously been emphasized is that earlier varieties have been produced by the plant breeders, and these are sufficiently free from frost damage to produce a crop which can fit permanently into the cropping systems of many Manitoba farmers.

Table XII shows the flax varieties that have been grown in the Prairie Provinces since 1910, together with the five-year period in which they were first introduced. The time of maturity, in terms of days from seeding to harvest, of the more commonly grown varieties from Table XII is as follows:

VICTORY	100	BISON	98
NOVELTY	100	PRIMOST	98
CROWN	99	DAKOTA	95
REDWOOD	99	BUDA	94
ROCKET	99	SHEYENNE	93
ROYAL	99	MARINE	93
		REDWING	91

It will be noted from Table XIII that REDWING, the earliest variety, occupied 60 per cent of the acreage in Alberta and that DAKOTA, a medium early variety, is popular in Manitoba and Saskatchewan. There does not seem to be much doubt but that the introduction of early varieties had an important effect on the popularity of the flax crop, particularly in Alberta and Manitoba.

A further factor which has made flax growing more successful is the

introduction of varieties with greater disease resistance. The first big step in this connection was the production, particularly by H. L. Bolley of the North Dakota Experiment Station, of varieties having greater resistance to wilt. These varieties, such as N.D. 115, BISON, and BUDA, were introduced into Canada shortly after their distribution in the United States and were undoubtedly a factor in making flaxseed production a safer farming proposition. The effect of wilt was of no importance in Canada when a large proportion of the crop was grown on new land but it made continuous cropping with flax very hazardous. The Manitoba soils, perhaps owing to moisture conditions, were more favorable to wilt than were Saskatchewan soils, and therefore the wilt-resistant varieties were of greater importance in that province.

Stem rust of flax became an important factor in flax production as the crop became concentrated in southeastern Saskatchewan and southwestern Manitoba. The variety BISON, which at one time occupied the greater part of the flax acreage in Manitoba, was very susceptible to stem rust and was very quickly replaced by the more resistant varieties as they became available. The varieties REDWING and ROYAL spread very rapidly and quickly replaced BISON. In more recent years there has been a wide distribution of DAKOTA and ROCKET, mainly because of their resistance to rust.

There are thus definite indications that, particularly in Manitoba, flax is taking a more permanent position as a seed crop. This is due in part to natural advantages of the soil and climate for flaxseed production together with chemical weed-control methods making the crop easier to handle, and in part to the introduction of earlier and more disease-resistant varieties.

TABLE XI

Acreages of Flax in the Chief Producing Areas[a] of Canada by 5-Year Periods, and Wheat:Flax Returns per Acre Ratio. Data in Thousands of Acres

Period	Ontario	Manitoba	Saskatchewan	Alberta	Canada	Wheat:flax returns
1910–14	8	62	1,157	91	1,318	1.18
1915–19	9	42	692	92	835	1.21
1920–24	10	148	685	37	880	1.13
1925–29	8	116	424	12	560	1.32
1930–34	6	62	340	22	430	1.47
1935–39	6	51	225	21	303	1.25
1940–44	20	188	998	220	1,426	1.21
1945–49	35	443	508	145	1,131	0.92

[a] Less Quebec, British Columbia, and the Maritimes.

TABLE XII

Chronological Record of the Distribution of Flax Varieties in Canada, to 1950

Period	Varieties				
Before 1910	PRIMOST,	N.D. 52,	NOVELTY,		
1910–14	N.D. 115,				
1915–19	CROWN,				
1920–24	BUDA,				
1925–29	BISON,	LINOTA,			
1930–34	REDWING,				
1935–39	ROYAL,				
1940–44					
1945–49	DAKOTA,	ROCKET,	SHEYENNE,	VICTORY,	VIKING,
1950	REDWOOD,				

TABLE XIII

Distribution of Flax Varieties in Percentage of Total Acreage in the Prairie Provinces in 1951

Variety	Manitoba	Saskatchewan	Alberta	Prairie Provinces
DAKOTA	54.2	25.6	9.1	26.1
REDWING	5.9	11.5	60.0	24.8
ROYAL	12.7	51.4	18.5	34.3
ROCKET	15.1	0.9	0.4	3.5
BISON	0.2	3.0	9.1	4.3
VIKING	0.3	2.7	0.5	1.6
SHEYENNE	7.3	0.8	—	1.8
VICTORY	2.8	1.9	0.7	1.7
Others	1.5	2.2	1.7	1.9

5. *Mixed Grains*

As will be noted from Table XIV, the mixed grain crops in Canada are grown mainly in Quebec and Ontario. Mixed grain as it occurs commonly in these areas consists of a 50:50 mixture of barley and oats. There has been a noticeable increase in mixed grain production in these two provinces during the past forty years. This seems to be due to more than one factor. In the first place the coarse grains are often fed to livestock in about a 50:50 proportion, and growing it in the mixed condition eliminates the need for separate storage space and the labor of mixing. It is also the opinion of many farmers that the growing of mixed grain spreads the risk and gives them better average returns. Field plot trials have failed to demonstrate that there is any advantage in mixing the grains from the standpoint of total production on a given

area. The barley crop in the eastern provinces seems to be more sensitive to soil and moisture conditions than oats, and therefore more variable in yield. For this reason the farmer is of the opinion that his best average returns are obtained by mixing the grains in the field.

TABLE XIV

Acreages of Mixed Grain in the Chief Producing Areas of Canada by 5-Year Periods. Data in Thousands of Acres

Period	Manitoba	Quebec	Ontario	Prairie Provinces	British Columbia	Canada
1910–14	12	102	356	5	2	477
1915–19	19	133	435	50	3	640
1920–24	26	135	609	54	5	829
1925–29	31	120	810	43	5	1,009
1930–34	32	116	969	61	3	1,181
1935–39	40	139	914	68	4	1,165
1940–44	65	237	1,024	156	6	1,488
1945–49	76	279	989	77	8	1,429

6. *Rye*

Rye production in Canada is confined chiefly to Ontario and the Prairie Provinces. In Ontario there have been wide fluctuations in acreage, but the acreage in 1910 was 93,000, and in 1950 it was 91,000; thus, there has been no general increase.

In the Prairie Provinces, in which the acreage in 1951, was 1,034,000, of which 694,100 was winter rye and 340,300, spring rye, there has been a very marked increase since 1910. In that year the total acreage was 10,000.

Violent fluctuations in the rye crop in the Prairie Provinces seem to be due in part to price changes. There was a rapid increase in production from 1910 to 1922, but the average farm price dropped from $1.28 per bushel in 1920 to $0.69 in 1921 and $0.55 in 1922. This was accompanied by a drop in production which reached a low in 1925. A similar and sudden drop in price occurred in 1930, and production dropped sharply in 1931. High prices from 1945 to 1947 again encouraged production, the acreage reaching an all-time high in 1948 of 1,965,000 acres, with a total yield of 22,350,000 bushels.

III. Field Husbandry, Soils and Agricultural Engineering

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1. *Acreages of Field Crops*

The major areas of agricultural production in Canada had been developed by 1918, and in the main have become more or less stabilized. Local changes may occur from time to time to meet changing circumstances, but on the whole over an extended period of years the differences are rather slight. Table XV, which supplements tables in the previous sections, shows the acreages in various field crops for the periods 1918–1938, 1939–1945, and 1946–1951, respectively.

TABLE XV

Acreage of Canada's Principal Field Crops,[a] in Thousands of Acres

Crop	1918–38	1939–45	1946–51
Wheat	22,772	23,573	25,101
Oats	13,827	13,410	11,947
Barley	3,660	5,872	6,702
Rye	903	914	1,135
Flaxseed	644	1,093	1,037
Shelled corn	208	247	249
Soybeans	—	39[b]	84
Dry peas	146	85	90
Dry beans	81	88	91
Mixed grains	994	1,402	1,471
Buckwheat	430	294	213
Potatoes	599	524	508
Sugar beets	49[c]	64	79
Field roots (turnips, mangels, etc.)	212	171	116
Hay and clover	9,649	9,381	9,801
Alfalfa	576	1,230	1,390
Fodder corn	490	479	527
Grain hay[e]	1,618[d]	911	857

[a] Without Newfoundland; statistical data not yet available for this province.
[b] First acreage reported 1934.
[c] First acreage reported 1933.
[d] First acreage reported 1923.
[e] Grain hay grown mainly in the provinces of Alberta and British Columbia. Reference: *Hand Book of Agricultural Statistics*, Part 1-Field Crops.

It will be noted that the wheat acreage has increased only slightly since the period 1918–1938. The period of World War II saw a slightly increased demand for wheat, and the acreage increased by approximately

1 million. New land has been developed in northern Alberta and Saskatchewan, and since the war the wheat acreage has increased by about 2½ million. The oat crop is a more or less standard feed crop, and the acreage has not varied greatly over the thirty-three–year period. The increased demand for barley for malting purposes and for livestock feed has been followed by increases in barley acreages in each of the three periods.

The demand for vegetable oils during the war period is reflected in the increased acreage of flaxseed, which has been maintained in the postwar period. The need of protein feed for livestock encouraged the production of soybeans during the war period, followed by an increased acreage in 1946–1951. Increase in livestock production has been followed by increases in mixed grain acreage as well as in alfalfa acreage during World War II and after. With the labor scarcity of war years and postwar years the acreage of field roots has decreased.

Trends in the future will no doubt be toward increased acreages of wheat and coarse grains and, to a lesser extent, of forage crops, as the Peace River area and areas in Northern Alberta, Saskatchewan, and Ontario are developed. The new emphasis on grassland farming will no doubt see an expansion in the acreage of pastures, grass silage, and hay.

2. Machinery and Equipment

The use of power on Canadian farms increased greatly with the expanding use of tractors in the period from 1918 to 1938. The Census figures for 1921 show 711,090 farms with 3.45 million horses and 47,455 tractors. By 1931 there were 728,623 farms and only 3.21 million horses, but tractors had increased to 105,360. There were an estimated 125,000 tractors by 1938. A major change occurred in tillage and harvesting equipment following the introduction of the combine harvester in 1922 and the one-way disc in 1927. By 1938 the one-way disc with seeding attachment had largely superseded the plow in the plains area. Use of the combine spread slowly at first, but by 1931 there were 8,897 in the Prairie Provinces and an estimated 11,000 by 1938. Combines were introduced into eastern Canada on a commercial scale with the sale of 35 units in 1937 and some 168 in 1938.

Expansion in the use of tractors in the Prairie Provinces in the 1920's posed many difficulties in economically fitting the size of equipment to the smaller farms, and this was a factor in increasing the size of farms. Similar problems occurred in eastern Canada after the introduction of rubber tractor tires in 1932, when sales of tractors rose rapidly. How-

ever, little or no general increase has taken place in the size of farms in eastern Canada.

In the period 1939–1945 farm output increased greatly, although there were fewer farm workers as well as limitations in the supply of new machines. Available materials were put into types of machines that would save the most labor; thus, there was a considerable increase in the number of tractors, combines, haying machines, and livestock equipment on farms in this period.

Immediately following the period of World War II the number of gainfully employed farm workers increased by about 200,000; however, with the heavy drain to industrial employment the number of farm workers again decreased by 250,000 to 1.02 million by June of 1951, the lowest in thirty years. Farm labor shortages, high costs, and a backlog of farm equipment requirements from the war period have resulted in an unprecedented demand for farm equipment since 1946. In the period of the past five years the sales of farm equipment have been about double the value of sales in the period covered by the previous eleven years, or 977 million dollars from 1947 to 1951 compared to 501 million dollars for the period 1936–1946.

It is estimated that in 1951 there were 8,000 hay balers on farms and 2,500 forage harvesters; that 130,000 motor trucks were in use by farmers, or double the number in use in 1941; that the number of farm customers of electrical companies approximately doubled during the period 1945–1949; that there were 100,000 combines on farms in 1951 and that the number of tractors on farms was upwards of 450,000. The 1952 demand for farm equipment is currently reported at 10–15 per cent below that of 1951, and it is expected this latter situation may continue into 1953.

3. *Agricultural Meteorology*

For many years the Department of Agriculture has maintained a close liaison with the Meteorological Service of the Department of Transport. The importance of meteorology to agriculture is immediately evident, as it is also in relation to transportation, building, mining, and many other industries. Meteorological records have been taken on all Experimental Farms and Stations across Canada as well as on many Illustration Stations. These records have been part of a much larger number taken at stations under the supervision of the Meteorological Service. In 1918 there were 600 meteorological reporting stations. By 1938 they had increased to 1000, and at present in 1952 there are 1200 such stations.

Meteorological data have been very helpful in agricultural research

work as well as for general farming. Information on frost occurrence is beneficial in determining the most suitable varieties of crops for use in the northern regions of the country and can be correlated with growth characteristics as affected by moisture, heat, and light relationships. Among the earlier correlation studies was that of moisture relationships in the somewhat arid section of the Prairie Provinces. In 1922 soil moisture experiments were set up at Swift Current. This work along with study of wind effects on soil drifting was expanded with the passing of the Prairie Farm Rehabilitation Act in 1935. These studies have had considerable beneficial effect on agriculture in relation to soil-drifting control, moisture conservation, the use of shelter belts, and other factors. The meteorological data are useful also in determination of crop adaptation and zonation; in land use and land settlement problems; and in general farm practices.

During the war years with the expansion in aviation and the setting up of a large number of airports and landing fields, meteorologists were appointed to make recordings and study various phenomena at practically all air fields. With this increased staff and the need for advanced information on flying conditions, great impetus was given to forecasting. This was later expanded to include local forecasts for agricultural purposes, which were very beneficial. Meteorological data have recently been invaluable in the study of the consumptive use of water for irrigation.

The future will probably see greater co-ordination between knowledge of climatic factors and the physiology of plant growth. Studies of the distribution of solar energy may be undertaken, as well as of the illumination intensity of light. A Central Weather Analysis Office has been developed in Canada and long-range forecasting is being studied.

4. *Irrigation*

In the early part of this century the first phase of irrigation developed in western Canada. During this period many small projects and several large developments were put into operation supplying water to some 300,000 acres. During the 1918–38 period the acreage under irrigation was expanded, and with the introduction of specialty crops, irrigation farming became established on a fairly sound economic basis. The prolonged dry period during the thirties brought the improved position of the irrigation farmer into sharp perspective and focused national attention on irrigation. In 1935 the Government of Canada passed the Prairie Farm Rehabilitation Act. One of the responsibilities of this agency was water development, and all major irrigation construction is now carried out under its auspices.

During the war period 1939–45 irrigation construction was curtailed, but surveys and plans for future development were carried forward. The reliable capacity of the irrigated area to produce food during the national emergency also was favorably noted.

Following the war, construction was begun on the St. Mary's River development. This entailed building the largest earthen dam in Canada and other appurtenant works to supply water to an additional 300,000 acres. This dam was officially opened in 1951, and further construction of smaller reservoirs, canals, and laterals is proceeding.

An important postwar development in irrigation has been the introduction of quick-coupling portable aluminum pipe. Systems of aluminum pipe with pump and motor to provide pressure have supplied farmers and market gardeners with a very convenient means of applying supplementary water to crops. More than one thousand such systems have been sold in Canada since 1946.

It seems apparent that there will be an increase in irrigated acreage in Canada. At the present time it is recognized by dominion, provincial, and municipal governments that the benefits of irrigation reach far beyond the individual farmers on the land; hence, national and provincial governments now share in the capital cost of irrigation construction. On this basis several large projects are now under active consideration.

5. *Pasture Management*

It was not until the late twenties that any systematic methods of pasture improvement were undertaken. Through the efforts of the Dominion and Provincial Departments of Agriculture and the agricultural colleges fairly extensive fertility and grazing management studies were laid down in eastern Canada and British Columbia. The fertilizer trials proved that pasture production could be increased economically by the application of commercial fertilizer. Nitrogen was given considerable prominence. The response to nitrogen, whether applied in one application in early spring or in split applications throughout the season, was proved to be affected largely by the clover population and the precipitation. With moisture plentiful split applications helped to distribute production more evenly.

It was shown that limestone on the surface of pasture swards is not as beneficial as when it is worked into the soil.

At three of the five stations, where rotational grazing experiments have been conducted on permanent pasture, production was increased slightly over that of continuous grazing. It helps to eliminate selective grazing and to promote a more desirable sward. The chief objection is the cost of extra fencing and water facilities. The use of the mower to

control weeds and long grass and of the harrow to scatter droppings was proved advantageous.

Intensity of grazing studies favored close grazing of permanent pastures early in the season with more moderate grazing as the season advances. Mixed grazing with sheep and steers, at a ratio of 4:1, gives a 30 per cent increase in production over single class grazing.

Supplemental pasture crops have been tested. Except in cases of emergency their cost has proved out of proportion to their value. With the introduction of the electric fence the practice of grazing the aftermath of hay fields has become widespread. In 1928 the work of regrassing abandoned fields, under dry-land conditions, was initiated at the Dominion Range Experimental Station, Manyberries, Alberta. Crested wheat grass gives a good cover.

In fertility experiments in the period 1939–1945 there was a trend towards higher fertilizer rates and more frequent applications. Phosphorus was usually the most needed fertility element.

Pasture in the crop rotation was shown to provide a more uniform carrying capacity than permanent pasture. In areas where drought periods are long the total seasonal production was higher from the pasture in the rotation.

Soil fertility experiments have been more extensive since 1946. Because the soil survey provided a basis for investigating the fertility requirements of the different soils, pasture tests in co-operation with farmers were established on different soil types. The fertility experiments have indicated that the greatest increases in yield from a single element have been obtained from phosphorus. Generally speaking, applications of nitrogen and potash have been less beneficial.

Rangeland investigations that are being conducted include grazing management studies of the native grasses as well as such valuable introduced species as crested wheat grass.

In the future it is anticipated that there will be less distinction between pasture, hay, and silage. Instead, the entire forage program will tend to be more closely linked together and planned in such a way that June surpluses may be utilized for silage or hay and the aftermath of silage or hay used for grazing. The larger grasses and legumes will be used more extensively. Management practices that will prolong the life of these species are worthy of investigation. Methods of improving farm pastures in western Canada will be studied in more detail. Irrigation practices on pastured land require a great deal of research and experience.

6. *Crop Rotations and Tillage*

a. Western Canada. Crop rotation in the Prairie Provinces in the main has followed a simple alternation of wheat and summer fallow or a three-year sequence of wheat, wheat (or other grain), and summer fallow.

High grain prices during, and immediately following, World War I stimulated an increase in wheat acreage in western Canada. Additional sod land was brought under cultivation, and there was a tendency to plant more wheat on stubble, thus reducing the acreage of summer fallow.

The continued dry period during the thirties brought about a return to alternate crop and fallow, since attempts to raise two crops in succession usually resulted in failure of the second crop. With improved moisture conditions and prices during and following the recent war there was some tendency to seed two crops following summer fallow. Since 1946 the trend has been to make use of an alternate crop and fallow system over much of the prairies. Such a system is more convenient for a farmer, since with half his land in crop and half in summer fallow he finds his labor load better distributed. However, alternate crop and fallow is probably not the most efficient use of land resources in that part of the prairie area where moderate rainfall is usually received.

In the mixed farming areas of the prairies longer rotations including hay crops are used: usually six- or eight-year rotations in which the hay crop is left down for two or three years. Hay production in the prairies

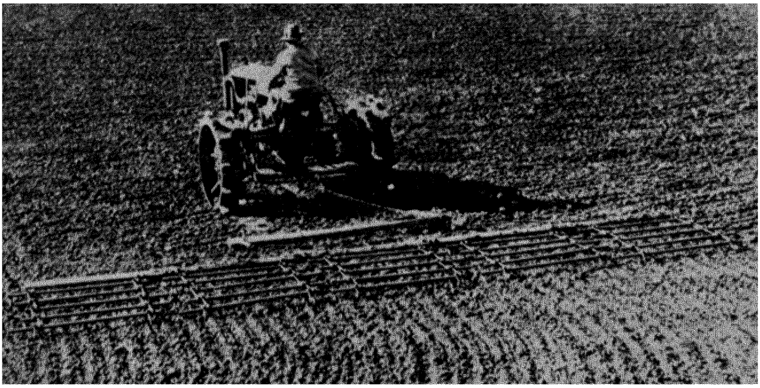

FIG. 2. Keeping the summer fallow "black" by cultivation to control weeds was the practice followed in the Prairie Provinces before the serious soil drifting in the 1930's.

registered a general increase from 1918 until 1945, the tonnage produced having doubled in that period. During recent years, however, a decline has been noted. This is accounted for by the fact that mixed farmers have been reducing livestock numbers and also reducing the amount of sod crops in the rotation.

Following the breaking of the prairie grasslands in the early part of the century the tillage pattern was largely simple plowing, cultivating, and seeding. Toward the end of the 1918–38 period soil-drifting problems practically forced the plow from the prairie. The old practice of

FIG. 3. Following serious soil drifting in the 1930's an attempt has been made to maintain a trash cover on the surface of the soil to protect from the wind.

a black summer fallow to control weeds gave place to that of a "trash cover." Plowing turned down all of the weed growth and crop residue and left the dry soil exposed to the wind, and blowing or drifting of the soil was encouraged. Machines such as the one-way disc, the duck-foot cultivator, and the rod-and-blade weeder were developed to keep the "trash" on the surface. Thus plowless fallow was introduced.

The introduction in 1946 of 2,4-D and other herbicides has further revolutionized tillage and weed control in the prairies. Some twelve million acres of land were sprayed or dusted with 2,4-D in 1950 and in 1951. This has reduced the need for tillage somewhat, but good farming and proper tillage are still the key to good production.

b. Eastern Canada. In eastern Canada crop rotations and tillage practices have become pretty well stabilized, and little change has occurred in the past half century. Over a large part of this area mixed farming is followed which necessitates the growing of grain and forage crops. In many areas a rotation of two years of grain and four years of hay and pasture constitutes the crop rotation. In some parts of Quebec and the Maritime Provinces swede turnips are grown for table use or livestock feed and in Ontario corn for silage is grown fairly extensively along with grain and hay in a six-year rotation. In the potato-

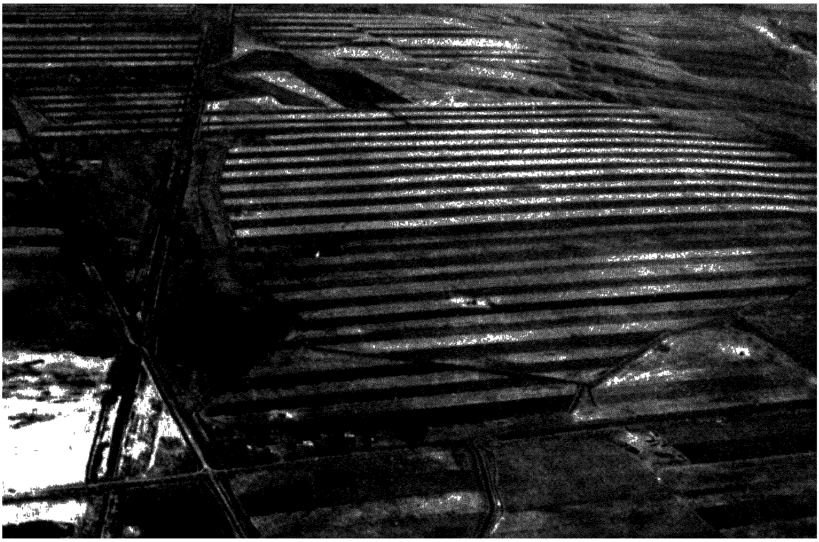

FIG. 4. Planting in alternate wheat and summer-fallow strips has helped to prevent soil drifting in some parts of the Prairie Provinces since 1935.

growing cash crop area of the Maritime Provinces a shorter three-year rotation of potatoes, oats, and clover prevails. This pattern has held during the war and postwar years.

In an area where such a large proportion of sod crops are grown the plow continues to be an essential implement. It is difficult to promote the decomposition of sod unless it is cut and covered. The more modern discs and cultivators do not handle sod satisfactorily unless it is previously plowed.

The trend is toward an even greater use of grass and legume crops. This is due to a consciousness that sod crops are excellent for soil conservation and also with respect to the economy of sod crops as pasture and silage crops.

7. *Soil Fertility and Fertilizers*

In a comparatively young country, agriculturally, such as Canada, the need for special attention to soil fertility has only recently become apparent. In eastern Canada it has now become the most important farm problem. Many of the soils were developed under evergreen forests. They were never particularly fertile even in their virgin state and were inclined to be acid in reaction. In the western Prairie Provinces, on the other hand, the soils in the southern areas were built up under a grass cover, and a considerable depth of fertile organic soil was available when the plow first broke the virgin sod. Furthermore, low precipitation in these areas limited production, with the result that fertility has not been used up so quickly. Very little response is obtained when commercial fertilizers are added in these regions, but in the more humid areas farther north some increases in yield are obtained from the use of commercial fertilizer.

In the early days of farming in Canada barnyard manure and green manure were the chief sources of added fertility. The Dominion Experimental Farm Service conducted some early experiments with commercial fertilizers, and an exhaustive experiment was conducted comparing different sources and rates of applying fertilizers as early as 1908. Another experiment comparing barnyard manure with commercial fertilizer and with a combination of the two was commenced in 1911 and is still in operation in 1952.

The value of phosphatic fertilizers for most soils and most crops became apparent almost immediately, and this ingredient is still required in relatively large amounts. Nitrogen and potash also give response on most soils and many crops. More recently deficiencies of trace elements are beginning to show in local areas. Deficiencies of cobalt, boron, manganese, copper, and magnesium are among those which have been observed.

The commercial fertilizer trade has developed considerably during the years since the early experiments. Very little was sold prior to World War I in 1914. After the war the busines began to develop but was retarded somewhat by the depression years of the 1930's. However, in 1933 a total of 166,407 tons of commercial fertilizer was sold in Canada. By 1938 the sales had almost doubled to 323,376 tons. During the World War II years 1939–1945, in spite of the quota system of fertilizer distribution by the Allies, increased production was essential, and by 1943 the amount used in Canada had increased to 535,534 tons. The increased use has continued until the year ending in June, 1951, when 770,507 tons were sold.

Another interesting trend in fertilizer usage is away from a system of home-mixing to the use of manufactured grades or analyses. In 1933 there were 82,374 tons sold as fertilizer materials and an almost equal amount, 84,033 tons, as mixed fertilizers. These relative proportions held until 1935. Then there was a swing to the use of a larger proportion of mixed goods. In 1946 almost six times as much fertilizer was sold as mixed fertilizer as compared with the amount sold as separate materials, and in 1951 about four times as much—616,574 tons of mixed fertilizer and only 153,933 tons of fertilizer materials.

One trend in the future is likely to be toward the use of more concentrated or higher-analysis fertilizer. There may be a trend toward spraying or dusting of trace elements on the crops rather than adding them to the soil, where some of them become readily "fixed." More economical methods of application may be developed.

8. *Soil Surveys*

a. Early Development. The earliest soil survey work in Canada was initiated by the Ontario Agricultural College some thirty-four years ago. However, it was not until the twenties that appreciable progress in this work was made, and the first published county soil survey maps in Ontario originated at this time.

In 1921, after a period of unsatisfactory farming conditions in Saskatchewan and Alberta, soil surveys were started in these two provinces under the direction of their respective colleges of agriculture. The Manitoba Agricultural College began the first organized soil survey in 1927, although some soil inspections and soil analyses had been made earlier. The first soil survey in British Columbia was made in the irrigation areas in 1931 by the British Columbia Department of Agriculture in co-operation with the Experimental Farms Branch of the Dominion Department of Agriculture.

In 1929 the Experimental Farms Branch offered financial aid for soil survey work to all the provinces that wished to avail themselves of such assistance. Unfortunately, soil survey work was discontinued in all provinces during 1932 and 1933 owing to a lack of funds. Work was resumed again in 1934 with provincial and dominion aid, and as a result of the Prairie Farm Rehabilitation Act, the scope of the work was greatly increased in the Prairie Provinces during the following years.

New surveys were organized on a co-operative basis between the provinces and the Experimental Farms in eastern Canada. In Quebec and Nova Scotia surveys were started during 1934 in market-garden areas on black muck soils and in apple-orchard areas. The first soil

survey in New Brunswick was commenced in 1938 and in Prince Edward Island in 1943.

Today soil surveys are conducted in all provinces through co-operation of the provincial departments of Agriculture, the agricultural colleges, and the Experimental Farms Service of the Dominion Department of Agriculture.

b. Improvement and Correlation of Methods and Techniques. The early soil surveys were based largely on the textural classification of the soils. However, as the more modern principles of pedology became known on this continent during the middle twenties, and as more scientific information regarding soils became available in recent years, these have been applied in soil survey work. As a result a gradual evolution has taken place over the years in the technique of surveying, as well as in the concept and interpretation of the established units and in their classification. It is, therefore, natural that the practical value and applicability of the survey results have become greater in the more recent surveys.

As the surveys developed it soon became apparent that, as in some provinces the work had been started independently, the approach to the problem and the classification of the soils varied considerably from province to province. This was due partly to local soil conditions but mainly to the concept held by the workers in the respective provinces. Consequently it has been difficult, especially for the uninitiated, to obtain a comparative country-wide picture of soil conditions by studying survey reports from individual provinces. This difficulty has been magnified by the adoption of different kinds of terminology in the individual provinces. In most cases the information obtained was authentic as far as the respective province was concerned, but often it did not lend itself to comparison from province to province.

Much progress has been made in co-ordinating soil survey work during the last ten years as a result of the establishment of a soil survey headquarters staff in Ottawa and the creation of a national Soil Survey Committee. Most of the differences in concept and approach to the work have been eliminated, so that it is now comparatively easy to correlate the work from province to province and to build up a country-wide picture of Canadian soil conditions.

c. Areas Surveyed. To give some idea of the progress of soil survey work in Canada, data are presented in Table XVI showing a typical year's survey work by provinces in 1951, together with the total area surveyed in Canada to date.

TABLE XVI

Areas Surveyed in 1951 and Total Area to Date in Acres

Province	Area surveyed in 1951		Total area surveyed to date
	Detailed	Reconnaissance	
Newfoundland	—	150,000	470,000
Prince Edward Island	—	—	1,397,000
Nova Scotia	26,300	600,000	5,800,000
New Brunswick	28,240	160,000	7,190,000
Quebec	16,500	755,000	22,200,000
Ontario	350	1,378,000	29,426,000
Manitoba	4,160	510,000	17,211,000
Saskatchewan	21,400	[a]	73,050,000
Alberta	370,000	1,080,000	72,000,000
British Columbia		550,000	8,300,000
Canada	465,950	5,183,000	237,044,000

[a] Exploratory surveys in northern unsettled areas—505 miles of traverses.

9. *Weed Control*

The years 1918–1938 may be described as the period in which interest in weed control was aroused. The results of moisture conservation experiments conducted at Swift Current, Saskatchewan, emphasized the necessity of controlling weeds in order to conserve soil moisture. A study of methods to control weeds was commenced soon after the Swift Current results were obtained.

In the period 1939–1945 much information was obtained about the behavior of weed seeds in the soil, in manure, and in silage as well as about the response of perennial weeds to different field practices. From the knowledge acquired from these experiments came recommendations on how to control weeds by cultural and cropping practices.

In this period, interest in chemicals for weed control was aroused. The herbicidal values of copper sulfate, iron sulfate, calcium cyanamid, and Sinox were investigated. The use of Sinox for the control of annual weeds in cereal crops became an accepted practice in some areas of western Canada and to a lesser extent in the eastern Provinces.

From 1946 to 1951 a phenomenal expansion in weed control occurred. It commenced with the introduction of 2,4-D in the year 1945 and with the discovery in the same year that this herbicide could be applied in a low volume of water. The spectacular weed control obtained, without injury to wheat, with the application of this new chemical in 5 gallons of water per acre was demonstrated on the Regina Plains in June, 1946, and caused so much interest in weed control in western Canada that the

acreage treated with 2,4-D in each succeeding year increased rapidly. In 1950, four years after this demonstration, 13,566,000 acres of cereal crops in the three Prairie Provinces were treated with 2,4-D for weed control.

In eastern Canada, because of the more diversified type of farming, 2,4-D has not been as quickly adopted as in the grain-growing area, but its use is gradually increasing.

This herbicide effectively, and at low cost, controls most of the broad-leaved weeds which infest cereal crops without seriously injuring these crops, provided it is applied at the recommended rates. There are some species of broad-leaved weeds which 2,4-D will not control. Couch grass, wild oats, and many other narrow-leaved weeds are immune to injury from 2,4-D. There is also the problem of controlling weeds in broad-leaved crops which are sensitive to 2,4-D. The search will go on for other chemicals to solve the many weed problems which yet remain.

IV. Forage Crops

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1. Regional Importance

With the wide diversity of soil and climate in Canada it would be expected that forage crops would also vary in different areas not only in their relative importance in general farm economy but in the range of adapted species. These questions can be discussed best by considering the four natural agricultural regions of Canada—the Maritime Provinces, the east-central provinces of Quebec and Ontario, the west-central Prairie Provinces, and British Columbia. Each of these natural divisions is not a distinct agricultural entity but must be further divided into zones with different capacities for forage crop production. These capacities compete with other agricultural crops, and the current balance at a given time period is the resultant of economic conditions as well as of soil and climatic factors. Consequently the situation in a given area does not remain static, but there is a constantly changing pattern. We will consider the relative importance and changing trends of forage crops in these four agricultural regions.

a. Maritime Provinces. Hay and pasture comprise 80 per cent of the total cropland in Prince Edward Island, Nova Scotia, and New Brunswick. This forage, marketed through livestock, provides about 30 per cent of the gross provincial agricultural revenues. According to the

Agricultural Census of 1951, 1.0 million acres were in hay and 1.8 million acres in pasture, of which 33.4 per cent was classed as improved. Prior to and during World War I, forage crops reached their greatest level of importance. Horses were still the main source of power on the farm, in towns, and for the booming mining and lumbering industries. There was a ready market for hay, and the farms carried considerable livestock. After the war conditions changed. Horses gradually were being replaced by mechanized equipment in other industries, and other

FIG. 5. Unimproved pasture in eastern Canada characterized by weed infestation and poor management, typical of many farm pastures twenty years ago.

farm livestock commanded only low prices. Field soils in general became depleted of nutrients, with consequent low productivity in hay and pasture.

In the present decade with a rise of farm prices, and in the prices of livestock products in particular, there is a gradually increasing application of good husbandry methods to restore the soil productivity and fertility. The use of lime to correct soil acidity is more common. This in turn has led to a better use of legumes in hay and pasture mixtures. The difficulty of curing good hay, coupled with the high cost of western grain concentrates, has led to a strong interest in the production of high-quality grass silage. Besides its value in conserving plant protein, the

use of silage has led to a decline in the use of swede turnips as winter succulent feed.

One phase of the hay and pasture picture is increased utilization of the considerable area of marshland (80,000 acres) built up by tides on the Bay of Fundy. Much of this choice land was dyked and reclaimed by the early Acadian settlers; however, in the course of time these dykes gradually fell into disrepair, with consequent reversion of large acreages. Under the Maritime Marshlands Rehabilitation Act government assist-

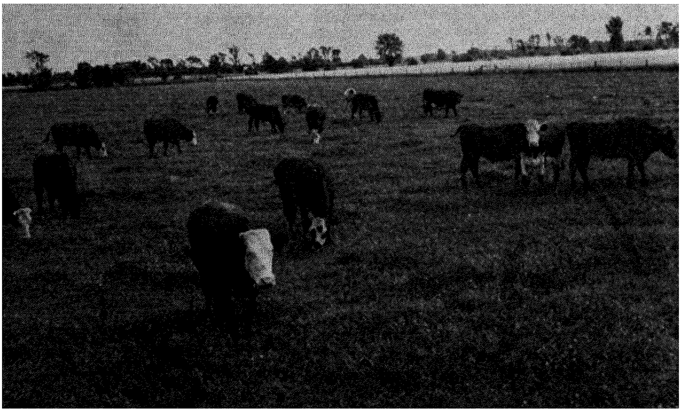

FIG. 6. Improved, well-managed pasture in eastern Canada—note freedom from weeds. The mixture consists of orchard grass, meadow fescue, alfalfa, red clover, and ladino white clover. This pasture is typical of present-day farm pastures in eastern Ontario.

ance has been extended for reclamation work. When the sea salts are leached out of the soil the native broadleaf grass (*Spartina pectinata* Bosc.) can be replaced by timothy, red clover, and alsike, and the deep fertile soil is capable of producing heavy crops. Regrassing studies are also being carried out on the seaward side of the dykes to prevent further soil erosion.

b. Quebec and Ontario. In the Quebec-Ontario region the raising of livestock is the main agricultural industry. In consequence, most farms have a high per cent of the land in hay, pasture, and fodder corn, with a small acreage of field roots. In the region as a whole, 7.1 million acres are in hay and 12.3 million acres in pasture, of which about 50 per cent is improved. By comparison in this region only 6.2 million acres are in cereal grains. The great bulk of the harvested hay, improved pasture, and coarse grains are consumed by the livestock on the farms. In addi-

tion winter feed is frequently supplemented by purchased protein concentrates.

There is wide variation in soil and climate throughout the agricultural areas of the region. The proximity of the Great Lakes tempers the climate in southern Ontario, but the climates of the northern parts of the two provinces are more extreme and are characterized by shorter growing seasons. Thus the frost-free period varies from 216 days at Harrow in southwest Ontario to approximately 145 days at Ottawa and less than 100 days in the northern agricultural areas served by the Experimental Stations at Kapuskasing, Ontario, and Normandin, Quebec. The soil types also vary from alluvial soil of lake shores and river flats to the glacial drift soils of southern Ontario and Quebec, the rough rock outcroppings in the Laurentian shield, and the clay belt in northern Ontario and Quebec. Although the rainfall over the whole area is adequate for good forage production, the soil and other climatic factors have pronounced effects on the use of plant species and the type of farm husbandry.

Southwest Ontario is mainly a cash crop area and the two crops, grain corn and soybeans (which are considered here as forage crops), have their greatest concentration of acreages. The good soil types of southern and central Ontario, the Ottawa valley, and the Eastern Townships of Quebec support the greatest concentration of dairy and beef cattle. In the latter areas there is the highest proportion of improved pasture, and the most productive species of legumes and grasses are utilized. In the rougher, partially wooded areas of the Laurentian shield, there is a higher proportion of unimproved pasture of low carrying capacity with a proportionately greater use of sheep than cattle. In wooded districts where lumbering is an important industry the farm occupants depend upon winter employment for cash income and the farm produce is supplementary.

The economic fact of the shift of population from rural to urban areas is having important effects on forage crop production. This shift has created a labor shortage that has caused many farmers to turn from dairy to beef farming, and many farms are being seeded down to permanent grass. Under dairy farming the tendency has been to use short hay and pasture rotations of three to four years, utilizing such species as alfalfa, red clover, timothy, brome, and orchard grass. In the permanent pasture the bottom grasses are dominant.

The labor shortage has also created a demand for types of machines that will lessen hand labor on farms. In hay harvesting the mower, side-delivery råke, hay loader, and hay fork, which represented distinct advances forty years ago, are being supplemented by field balers. Where

grass and corn silage are produced the forage crop harvester is considered essential equipment.

c. Prairie Provinces. In the grain-producing areas of the Prairie Provinces, forage crops are regarded as of only minor importance. In such areas only about 2–4 per cent of the cultivated land is sown to cultivated forage crops. In irrigated sections, however, forage crops such as alfalfa assume a more important place. Around the periphery of the major wheat-growing area, cultivated grasses and legumes are utilized on from 8–10 to as high as 20–30 per cent of the improved land. On the outer northern fringe of settlement, seed production of one or more forage crops is a major enterprise.

The relative proportions of forage crops grown in these areas, small as they are, represent substantial increases in the last two decades over those obtaining during the homesteading period. These increases are fairly general and are not confined to particular areas. They represent the use of cultivated forages for hay and pasture to replace diminishing natural grassland resources. These increases also include acreages devoted to the production of grass and legume seed, which in certain sections gives surer although less spectacular returns than those from cereal grains.

The grass and legume species that have contributed to this changing picture are relatively few. By 1930 the merits of crested wheat grass for semiarid areas were recognized, and the distribution of the grass became general as the seed supply situation improved. In the prairie areas of greater rainfall the ability of the alfalfa-brome mixture to produce a high yield of good quality forage won it a premier place. Sweet clover, slender wheat grass, and reed canary grass are also grown to a lesser extent. The practice of fall rather than spring seeding has improved the chances of good establishment with these forage species.

d. British Columbia. The mountainous terrain of British Columbia, associated with varied conditions of soil and climate, has led to considerable diversity in types of farming. If the province as a whole is considered, the livestock population relative to the proportion of cultivated land is high, and forages are therefore the leading field crop. In making a broad assessment of forage use the province may be divided into three major zones: the coastal, the south-central, and the north-central regions.

In the coastal region 70 per cent of the cultivated acreage is to be found in the narrow valley at the mouth of the Frazer River, and the remaining 30 per cent on the coastal plain of southern and eastern Vancouver Island. This region possesses a maritime climate with relatively high precipitation having its lowest fraction in the summer months. Dairy farming is conducted on an extensive scale, and forages are basic

to the area, making up fully two-thirds of the farmed acreage. The dominant species for pasture are orchard grass, perennial rye grass, Kentucky bluegrass, reed canary grass, and meadow fescue. Wild white clover is the leading pasture legume, followed very closely by ladino clover. For hay purposes, the grasses mentioned above, together with timothy, annual rye grass, and red top, are used. Red clover is the leading hay legume, although the use of alfalfa is increasing on well-drained soils. Winter feed is stored as hay, supplemented by silage consisting mainly of corn and, to a lesser extent, of oats, peas, and vetch.

The valleys of the southern interior are arid, and alfalfa is the principal crop being grown under irrigation as winter feed for the ranching industry. High-quality irrigated pastures are a new development in the southern interior, and their use is expanding rapidly. Orchard grass, Alta fescue, and ladino clover are the principal species in such pastures.

The central interior plateau and contiguous valleys are characterized by long winters and comparatively cool growing temperatures. Much of the area remains in a pioneer stage of development. Alsike clover and timothy seed are leading cash crops, and the threshed roughage is used as winter feed. The Peace River block to the east of the central interior plateau is in reality a separate zone. Here the production of alfalfa for seed has become a thriving industry in recent years. Creeping red fescue grows exceptionally well and is valued for both forage and seed. The use of the brome-alfalfa mixtures for hay is increasing.

2. *Breeding Accomplishments*

Previous to 1918 forage crop improvement programs in Canada were mainly confined to the two older agricultural colleges at Macdonald College, Quebec, and Ontario Agricultural College, Guelph, Ontario. It was not until 1912 that forage work was recognized as of sufficient importance in the Dominion Experimental Farms Service to establish a separate division to carry on work. Later projects on testing varieties for yield and adaptation were carried out at the branch experimental farms and stations distributed throughout the provinces. In 1932 a Forage Plant Breeding Laboratory was established at Saskatoon, Saskatchewan, to carry out breeding work pertinent to prairie conditions. At the beginning of the 1918–1939 period universities had been recently established in the four western provinces, and their affiliated agricultural colleges soon had research projects in forage crops under way. In this period there was formulation of comprehensive plans for the organization of research work with the main species of grasses, legumes, hybrid corn, soybeans; sunflowers, field roots, and turf grass. A limited number of improved varieties was released for distribution in this period.

The forage crop improvement program was not seriously interrupted during World War II, although it was somewhat handicapped by a shortage of technical staff and by the necessity of devoting time to special problems growing out of the war. One such problem was the development of oilseed crops such as rape and sunflowers. The acreage devoted to soybeans was greatly increased. The necessity of the rapid establishment of airports in connection with the Commonwealth Airtraining Scheme also required the assistance of forage crop specialists in rapid turfing establishment and maintenance.

In the period from 1945 to the present the earlier projected plans have been prosecuted with vigor. The natural fruition has been the production of a relatively large number of improved varieties suited to our diversified soil and climate. The future should see a continuing extension of this work.

The breeding work in forage crops has been subject to changing objectives. The development of hardy varieties of perennial and biennial legumes and grasses was an early objective as well as the development of early-maturing varieties of such annual crops as grain corn and soybeans. These objectives have been attained for the areas now cultivated, although the work is continuing with the extension of the agricultural frontiers northward. In the older cultivated areas the incidence of disease and insect pests is increasing, and current breeding projects are designed to develop immune or highly resistant varieties. The increasing use of labor-saving machinery such as harvesting combines has introduced problems in producing varieties suitable for such operations. Freedom from shattering, uniformity in maturity, and a minimum of lodging are characteristics sought to meet such changing husbandry practices.

There is also a changing pattern in breeding methods throughout the years. In earlier years mass selection was largely practised, and varieties superior to commercial varieties were produced by such methods, but, with more exacting needs, more refined and technical methods must be followed. Selections are now evaluated on the basis of a test of inbred and outcrossed progenies. The superior plants are combined into synthetic strains by controlled crossing or by growing the selections in isolated plots. If disease resistance is a desired character, the susceptible selections are eliminated in a disease nursery.

The actual source of Canada's economic forage species is of interest. Most of the cultivated grasses and legumes for hay and pasture use have been introductions of European origin. The most important introduced grasses are: timothy, Kentucky bluegrass, orchard grass, and brome grass in eastern Canada; crested wheat grass and brome in the prairies area in

western Canada; and perennial rye grass and orchard grass in the more humid areas of British Columbia. Improvement work has been carried out with very few of the native species of grass, although notable exceptions are reed canary grass (*Phalaris arundinacia*), slender wheat grass (*Agropyron pauciflorum*), and turf selections of *Agrostis* spp. All the important legumes under cultivation were introduced. These are alfalfa, red clover, white clover, sweet clover, and alsike. Birdsfoot trefoil, which is currently being tested, may prove of use in areas where alfalfa is not well adapted.

a. Improved Varieties. 1. Alfalfa and clovers. Variegated alfalfa (*Medicago media* Pers.) is the only alfalfa species possessing sufficient hardiness for Canadian conditions. GRIMM, brought to the United States by a German immigrant, Wendelen Grimm, was introduced to Canada early in the present century, and it or selections from it such as GRIMM SASK. NOS. 451 and 666 are still the most widely grown. A variety grown for many years in eastern Canada, ONTARIO VARIEGATED, was introduced from France seventy-five years ago, but owing to lack of suitable seed-growing areas it has been largely replaced by GRIMM. Varieties that have been developed for outstanding hardiness are VIKING, GRIMM SASK. NO. 451, and LADAK. Varieties for outstanding seed production are GRIMM SASK. NO. 666, FERAX, and CANAUTO. Another variety developed as a good pasture type is RHIZOMA. Several factors have combined to limit the wider use of these newer varieties. The best seed-producing areas are in the northern cultivated portion of the prairies, where to prevent admixtures it is better to limit the growers to one or two proved varieties (such as GRIMM and LADAK) that also command an export market. Bacterial wilt and crown rot of alfalfa are becoming increasingly prevalent in Canada, and none of the varieties enumerated above has complete resistance to these diseases. Consequently a very active breeding program is now in progress to combine disease resistance and hardiness in the same strain. This work is cooperative, involving plant breeders at several experimental stations as well as plant pathologists. It is anticipated that when these strains are available for distribution, all the varieties currently grown will be replaced.

Red clover is the most important legume in eastern Canada. Hardy, persistent, productive double-cut varieties such as DOLLARD, OTTAWA, and REDON have been developed from material first introduced from Europe. The single-cut varieties, ALTASWEDE, MANHARDY, and M.C. LATE, are grown in northern areas of shorter season. These varieties were largely the result of mass selection but further improvement is being sought, particularly resistance to disease, by controlled hybridization of selected plants and progeny tests.

Another legume, white clover, which was probably introduced, though it is now very widespread, has a very useful place in pasture. A white clover strain, PATHFINDER, has been selected from indigenous material which is comparable to the Danish strains, MORSO and STRYNO, in growth habit. Ladino, a giant form of white clover, recently introduced from the United States but originally from Italy, is proving very useful in humid and irrigated areas.

Sweet clover is one of the most important legumes in the Prairie Provinces and to a certain extent in eastern Canada. It is valued not only as forage but also for its soil-improving properties. It has, however, several faults which the plant breeder is trying to eliminate. These are hard-seededness, the bitter constituent coumarin, and its coarse branching habit. Dwarf mutant types such as ALPHA and BRANDON DWARF are more desirable for hay on areas of good rainfall than the coarser varieties such as ARCTIC, ZOUAVE, AURA, and ERECTOR. An annual form called MELANA, resembling ALPHA, is characterized by a profuse and prolonged blooming period making it attractive as bee pasture.

2. Grasses. Considerable progress has been made in grass improvement in the last two decades. In timothy the hay varieties, BOON, CLIMAX, DURAL, MEDON, MILTON, and MONTCALM, have been selected for yield and rust resistance. They vary in maturity from early to late. In orchard grass the varieties AVON, HERCULES, and ORON have been selected for hardiness, yield, and late maturity. In meadow fescue, ENSIGN, STURDY, and MEFON have improved yield, uniformity, and good seed habit. In perennial rye grass, PACIFIC and PERON have been selected for leafiness, hardiness, and resistance to disease. In brome grass, PARKLAND has been selected towards a less strongly creeping habit. FAIRWAY crested wheat grass has been selected for leafiness and drought resistance. This species is diploid ($2n=14$), whereas the normal species is tetraploid. In Kentucky bluegrass, the varieties DELTA and KENON have been selected for dual hay and pasture purpose. DELTA owes its uniformity to its apomictic seed habit. The varieties CHIEFTAIN and CANON in Canada bluegrass are proving of value in thin sandy soils and certain clay types. Breeding work is also in progress with several additional grass species which introductory tests have shown to be useful. These include species of AGROPYRON, ELYMUS, and FESTUCA.

3. Corn and soybeans. Breeding of corn is now being conducted at five stations in Canada. These stations, together with the year in which the breeding work was begun, are as follows: Macdonald College, Quebec (1922); Manitoba Agricultural College, Winnipeg, Manitoba (1938); the Dominion Experimental Stations at Morden, Manitoba (1938), Harrow, Ontario (1923), and Ottawa, Ontario (1928). At all stations except

Macdonald College the breeding work has been directed towards the development of hybrids for grain production. At Macdonald College the work has emphasized largely the production of hybrids for silage.

Most of the grain corn is grown in Ontario, with the largest acreages in the southwest. Corn for ensilage purposes is more widely grown, on approximately double the acreage devoted to grain corn. Ottawa and Harrow have concentrated on the breeding of grain corn hybrids, the former station for earliness and the latter for varieties to utilize best the longer growing period of southwestern Ontario. In addition to maturity the objectives include uniformity of maturity for mechanical picking and resistance to lodging and disease. Each in the series of corn hybrids produced at Ottawa is called CANBRED, and the following are licensed: 130, 150, 210, 220, 250, and 260. Each in the series of hybrids produced at Harrow are called HARVIC, and the following are licensed: 333, 482, and 485. After production and testing the hybrids are turned over to commercial companies for increase and distribution, although the research institutions maintain the stocks of the hybrid constituent inbred lines. The services of the Ontario Hybrid Corn Committee should be mentioned. They conduct co-operative tests of corn hybrids produced in the United States, and the most suitable are licensed for sale and distribution in Canada. Many of the later-maturing grain hybrids serve for ensilage corn in zones where they normally do not mature grain corn.

Macdonald College has produced two outstanding varietal corn hybrids which are widely grown in Quebec for ensilage purposes—IROQUOIS and ALGONQUIN. The former is a cross between QUEBEC NO. 28 and STOWELL EVERGREEN; the latter, a cross between QUEBEC NO. 28 and WISCONSIN NO. 7. In recent years the work has been concentrated on ALGONQUIN, which has proved the more useful of the two varietal hybrids.

Improvement work with soybeans was begun in 1894 at the Ontario Agricultural College, Guelph, Ontario. This resulted in the selection and release of the variety O.A.C. NO. 211 in 1920. Breeding work, started at the Dominion Experimental Station, Harrow, Ontario, in 1923, and at the Central Experimental Farm, Ottawa, Ontario, in 1928, has resulted in the following soybean varieties being released for production in the subsequent period 1933–1951: MANDARIN (Ottawa), KABOTT, PAGODA, and CAPITAL from Ottawa; A.K. (Harrow), HARMAN, HARLEY, and HAROSOY from Harrow. These varieties vary in maturity from approximately 90 to 135 days. Additional varieties, which have been introduced from the United States and are now being grown in Canada, include the following: EARLYANA, LINCOLN, HAWKEYE, BLACKHAWK, MONROE, FLAMBEAU, and a few others of lesser importance.

3. *Production Trends*

In the discussion of the regional importance of forage crops a few general trends were indicated towards a fuller utilization of forage crops. There have been outlined under breeding achievements the objectives of production of more satisfactory varieties of forage crops which would persist and yield well under a wider range of soil and climatic conditions. In the present section we will treat the forage plant species more particularly, giving a brief outline of their increasing or declining importance. A short history of ranching developments in western Canada will conclude this section.

a. Grasses. From the time of the early colonization of eastern Canada, timothy has been the leading hay species. This leading position is still maintained today to the extent that there is more timothy seed utilized in hay and pasture mixtures than all other grass species combined. The reasons appear to be the high adaptability of the species, its ability to grow well in association with legumes, a cheap and plentiful supply of seed, and the ease of establishment. It is likely that the acreages devoted to hay and pasture in eastern Canada will remain fairly static in the future. Consequently, relatively new hay and pasture grasses will make their gains at the expense of timothy and must be demonstrably superior in one or more characteristics. Certain species do possess these characteristics and have proved better legume associates in certain areas and under certain conditions.

Orchard grass for a high-production pasture grown in association with ladino clover on the irrigated land in Alberta and British Columbia has won well-merited recognition. It is also entering more into hay and pasture mixtures in eastern Canada. Its use was at first restricted to Western Ontario owing to a lack of winter hardiness, but with the production of such hardy varieties as HERCULES it can now be grown in Eastern Ontario and Quebec. It possesses more drought resistance than timothy and recovers more quickly after mowing or grazing.

Brome grass grown in association with alfalfa is the leading hay grass in the moister prairie areas and the Peace River block. In eastern Canada brome grass has not been more widely used chiefly because it is difficult to sow with other small-seeded forage species, as it will not run through the grass seed box attached to the standard grain drill. If it is mixed with the grain and seeded shallow on a firm seedbed, establishment is reasonably certain. It is drought-resistant and more palatable than orchard grass in its later vegetative stages.

Reed canary grass fills a need for a good grass in wet situations such as bottom land and peaty soils where other grasses fail because of ex-

cessive moisture. Although especially fitted for such an environment, it also does well on well-drained soils, where it is hardy and persistent. It is indigenous to Canada and has a local usefulness in practically all areas.

Although the above species are the principal hay grasses or dual hay-pasture species, there is a group of species of the so-called bottom grasses whose use is recommended in permanent pastures. Some of these grasses being indigenous will be components in such a pasture whether seeded or not. Meadow fescue (*Festuca elatior,* L.) grows well in association with other grasses and legumes, possesses a large percentage of palatable basal leaves, is easy to establish, and is persistent when the soil is reasonably fertile. New improved varieties are available. Kentucky bluegrass (*Poa pratensis,* L.) is so widely distributed that it is regarded as indigenous and is the dominant species in natural pastures on non-acid soils in Ontario. It produces an early growth but tends to become dormant in periods of drought. Brown top (*Agrostis tenuis,* Sibth.) or colonial bent is frequently the dominant species in natural pastures on acid soils in the Maritime Provinces and is generally associated with white clover. It is not so aggressive as Kentucky bluegrass in a mixture and tends to occupy small patches of ground. Red top (*Agrostis alba,* L.) occurs naturally in large areas in eastern Canada, particularly in the Eastern Townships of Quebec. It is less palatable than most grasses although well grazed when grown in combination with white clover. It is particularly suited to poorly drained soils. Creeping red fescue (*Festuca rubra,* L.) is one of the most popular of the small fescues. It is quite winter-hardy, and although unproductive in drought periods, it resumes its growth quickly when moisture becomes available. Meadow foxtail (*Alopecurus pratensis,* L.) is characterized by very early spring growth; it grows well in mixtures, is palatable in its leafy stage, and thrives in low-lying clay soils. Its poor seeding habit and its difficulty to sow has restricted its use. Canada bluegrass (*Poa compressa,* L.) occurs naturally in areas in Ontario, such as dry infertile meadows and waste places, where other grasses fail. It does not compete well in mixtures of other grasses except in areas that favor its adaptation.

In western Canada early plant breeding work developed good strains of the native species, slender wheat grass (*Agropyron trachycaulum,* (Link.) Malte). This species possesses several merits that led to its wide distribution for a time. The pasture and hay are fairly palatable, its seeding habit is good, and it is highly alkali-tolerant. But since the introduction of crested wheat grass (*Agropyron cristatum,* (L.) Gaertn.) slender wheat grass has been largely replaced. Crested wheat grass, although it possesses outstanding merits in the semiarid areas occurring in portions of the southern Prairie Provinces, has proved of little value

for hay and pasture in eastern Canada. Its value and limitations will be pointed out in the discussion of the ranching situation.

b. Legumes. Red clover still ranks as the leading legume in eastern Canada, its history and prominence being very similar to those of timothy. Like the latter it is widely adapted and the seed is in plentiful supply; it also associates well with timothy and is easy to establish. Although defined as a short-lived perennial it is usually treated as a biennial. In addition to being a good hay and pasture species, it makes good silage.

Although red clover will always occupy an important place, the present trend is towards a greater use of alfalfa. In Canada as a whole the alfalfa acreage increased from 0.3 million acres in 1922 to 1.5 million acres in 1949, of which at least 50 per cent is in Ontario. The acreage has, however, also substantially increased in other provinces. It is hoped as a result of current breeding work to extend the alfalfa acreage in the Maritime Provinces by the development of a variety tolerant of acid soil conditions. The high yield and feeding value of hay and pasture containing this legume component are the chief reasons for its increasing popularity. No legume species withstands so well prolonged periods of summer drought.

A few lesser trends are worth mentioning. Ladino white clover, a comparatively new introduction to Canada, is proving highly productive in areas where severe winters and prolonged drought are not limiting factors. Birdsfoot trefoil (*Lotus corniculatus*, L.) is finding a useful place in areas not suited to alfalfa. Sweet clover, the popularity of which has declined in recent years, is proving of value as a remedial crop in southwestern Ontario. In clay areas devoted to the culture of cash crops (grain corn, soybeans, vegetables, and others) the rotational use of sweet clover is very effective for improving the physical condition of the soil.

In western Canada the two main legumes for hay and pasture use are alfalfa and sweet clover. Smaller areas in southern Manitoba, central Alberta, and the Frazer valley of British Columbia are adapted to red clover. Two special developments connected with general legume economy are worthy of comment. Practically all the Canadian-grown seed of alfalfa, sweet clover, and alsike is now produced in the northern cultivated areas of the Prairie Provinces. Favorable factors for this exist in the grey-wooded soil zone in which vegetative growth is restricted and abundant bloom promoted with plentiful populations of wild bee species. This seed industry is well established and still capable of considerable expansion. The second development is use of such legumes as alfalfa and ladino clover on irrigated land. As more and more irrigation developments convert semiarid areas into highly productive farms, this trend

should assist in giving permanence to the dairy industry as well as enable the rancher to finish his livestock in feeding lots in the fall and early winter.

c. Corn and Soybeans. Previous to 1938 only open-pollinated varieties of corn were grown in Canada. The replacement of open-pollinated varieties with hybrid corn was so rapid during the years immediately following 1938 that by 1945 at least 95 per cent of corn acreage planted for grain production was of the hybrid type. In 1951, practically all the corn planted for grain production was hybrid, whereas it is estimated 60–70 per cent of the corn planted for silage use was likewise of hybrid origin. The change-over from open-pollinated to hybrid corn has been the most outstanding feature of corn production in Canada. The area planted to grain corn in Canada is about 250,000–300,000 acres; that in silage corn is 600,000–700,000 acres. Whereas the production of grain corn may reasonably be expected to increase in the future with the increasing availability of early-maturing hybrids, the acreage devoted to ensilage corn is not likely to do so because of the increasing use of grass silage.

The soybean was a relatively unimportant crop in Canada until 1942, with the area planted annually previous to that time not exceeding 10,000–20,000 acres. In 1942 it increased to 42,000 acres, and since then has gained steadily until in 1951 there was planted 176,000 acres, yielding 4.4 million bushels of soybeans valued at 11–12 million dollars. With the present active demand for soybeans and soybean products it is expected that the acreage devoted to the soybean crop will continue to expand. The 1951 production of soybeans amounted to less than 50 per cent of the domestic consumption.

d. Range Development. Range grazing in western Canada commenced about 1865 in the interior of British Columbia. The industry expanded rapidly throughout the western prairies until farm settlement pre-empted districts suitable for field crop production. Since about 1910 there has been a gradual withdrawal of the range industry from the arable lands.

Early management attempted year-round grazing, but soon modified the system to one which provided for winter feed reserves. The first reserves consisted largely of native hay, but cereal hay straw and grain soon became a popular winter feed. In certain districts today cereals, principally oats and rye, provide as much as 80 per cent of the winter feed supply.

Overgrazing of summer fields became widespread by 1920, and led to the establishment of an experimental program to study range production and management. This work was inaugurated in 1926, and dur-

ing the succeeding decade it established the basic principles of sound range management. Outstanding findings of this research program, which are being incorporated into ranch and community pasture management, include:

1. Carrying capacity can be maintained by conservative stocking.
2. Moderate continuous grazing throughout the summer is preferable to seasonal rotations.
3. Stockwatering sites should not be more than 2½ miles apart.
4. A carryover needs to be maintained to stabilize production and to build pasture reserves.
5. Supplementary pastures for spring grazing increase carrying capacity.

A grazing survey was inaugurated in 1937, and by 1945 had classified the western range lands on the basis of plant cover and average production. Five important associations were described and mapped in part. These associations were called the short, mixed, true, submontane, and Palouse prairies after their counterparts in the United States. Carrying capacities vary from more than 5 acres per cow-month in the short grass, to less than 1 acre per cow-month in the submontane. These experimental findings have been used to guide assessment programs.

Since about 1935 crested wheat grass (*Agropyron cristatum,* L. Beauv.), has been used extensively to regrass abandoned farm land. It has been accepted as an excellent spring pasture, as 2 or 3 acres replaces 10 or 15 acres of native range prior to mid-June. The acreage increase of this crop was the major trend on range during the decade following its introduction.

Use of new grasses and legumes for seasonal pasture supplements appears to be a trend that is developing. Proved new pasture crops include *Elymus junceus,* Fisch., and *Agropyron intermedium* (Host) Beauv. Both provide satisfactory late summer and autumn pasture.

V. Horticulture

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1. *Horticultural Trends*

The development of commercial horticulture in Canada has been largely determined by climate, although available markets have had an influence. Thus, in the very early years apples were grown on a comparatively large scale in the Annapolis Valley of Nova Scôtia because the climate and soil were naturally adapted to this crop. By 1939 the

growing of this fruit had expanded to big business because of the available market in Great Britain, coupled with the ease and low cost of transportation. A small fruit and fresh vegetable industry was flourishing in New Brunswick because of climate and the demands of the home market.

An apple industry was established and growing rapidly in the southwestern portion of Quebec. In Ontario apple growing was either static or declining, but the tender tree fruit industry located in the Niagara peninsula and the Essex peninsula was flourishing in the only part of eastern Canada where the climate would permit it to flourish.

The apple growers of British Columbia in the Okanagan and adjacent valleys had built a very progressive apple industry and were not only expanding it but also expanding in tender fruits, such as apricots, peaches, and cherries.

Small fruits, such as strawberries, raspberries, and currants, were being grown on a commercial scale in all provinces, with British Columbia on an export basis. Vegetable production had developed near all the larger consuming centers, to supply local demand for fresh vegetables.

The processing or canning industry was well established in Ontario, Quebec, and British Columbia, and towards the end of the period some development was under way in Manitoba and southern Alberta. The southern Alberta development was activated by the availability of irrigated lands and an ideal climate for pea production.

The period of 1939–45 introduced a heavy demand on Canada for all kinds of food, excepting apples, which, owing to the loss of the British market, were in surplus supply. This increased demand was accompanied by a decrease in available manpower, which gave impetus to the trend toward increased mechanization. Thus many crops formerly grown by market gardeners on comparatively small areas with an excess of hand labor were handled in larger fields by less labor and more machinery.

The surplus situation in apples resulted in the removal of some 1 million trees from the Nova Scotia orchards in an endeavor to balance production with available demand. At the same time in this province efforts were made to expand cold storage facilities, improve packing arrangements, and change over to varieties more popular on the home market.

The heavy demand for other foodstuffs resulted in the establishment of eight or ten large plants for the dehydration of vegetables, most of which have been closed since 1946.

In this war period there was price control in Canada, so that beyond

the increased demand for most commodities, met largely by increased mechanization, no very marked changes occurred in Canadian horticulture beyond those mentioned above.

The period since 1945 should actually be included in the one just discussed because we are now witnessing the results of the economic changes brought about by the 1939–45 period. The continued absence of the British market for apples has resulted in the reduction of the Nova Scotia apple industry from 21 per cent of the provincial agricultural income in 1938 to 3.3 per cent in 1951. Increased costs have been reflected in increased freight rates, which in turn have made it less profitable to ship certain processed foods long distances. This situation has resulted in processing plants being established in regions which were formerly importers of processed fruit and vegetables. Although complete statistics are not available for all provinces, the following will serve to point up this trend.

TABLE XVII

Percentage Distribution of Factory Selling Value of Total Pack of Canadian Canned Fruits and Vegetables

	Av. 1931–38		Av. 1939–45		Av. 1946–50	
	Fruits	Vegs.	Fruits	Vegs.	Fruits	Vegs.
Ontario	74.0	60.9	56.4	56.7	60.6	53.0
Quebec	0.8	24.1	1.7	24.4	0.9	25.2
British Columbia	18.3	13.3	29.7	12.4	30.4	11.5
Other provinces	6.9	1.7	12.2	6.5	8.1	10.3
	100.0	100.0	100.0	100.0	100.0	100.0

In 1931-38, fruit was 25.2% of the total canned pack value; in 1939-45, 24.0%, and in 1946–50, 29.6%.

It will be noted in Table XVII that whereas Ontario in period no. 1 accounted for 74 per cent of Canada's processed fruits, its contribution had dropped to 60.6 per cent in the third period, whereas that of British Columbia rose from 18.3 per cent to 30.4 per cent. In processed vegetables Ontario dropped from 60.9 per cent to 53 per cent, British Columbia dropped from 13.3 per cent to 11.5 per cent, and the total of other provinces rose from 1.7 per cent to 10.3 per cent. The latter increase was largely due to increased vegetable production for processing purposes in Nova Scotia and Alberta. This trend towards increased horticultural production in "Other provinces" is still continuing. In Ontario, in particular, industrialization is taking over large tracts of the most desirable horticultural land, much of which cannot be replaced. Thus industrialization in the Niagara peninsula is taking over land in a region

which enjoys a climate suitable for tender fruits and which has been the center for this type of production in eastern Canada. If this area should become completely industrialized, eastern Canada would be on an import basis for a number of commodities. In other parts of Ontario the inroads of industry are also apparent. In one instance alone, 1500 acres of farmland were taken over and put out of production; included in this was about 125 acres of apple orchard.

Much of the land being industrialized is the better agricultural land, the loss of which forces the removal of those producers who wish to continue to less desirable property.

The effect is twofold: less area for agricultural production and more population to demand agricultural supplies. It is unfortunate that less desirable land for agricultural purposes could not be used for this industrial expansion.

No picture of Canadian horticulture would be complete without some special reference to the horticulture of Prairie Canada. Much of the horticulture of this region has had to be created by the breeding of new varieties adapted to the dry conditions and severe winters of that region. There has been a very marked increase in vegetable production within the last ten years owing to these newer and more adaptable sorts, and the growing of many fruits in the Prairie home garden has become quite common practice. In former years many citizens of these provinces looked upon their sojourn there as temporary. Now, largely as a result of an improved horticulture, they expect to live there permanently.

2. Changing Methods

Most of the period 1918–38 was comparable to the horse and buggy days. Power equipment was becoming quite common for spraying around 1918, but it was largely drawn by horses; orchard operations were carried on largely by horses at the beginning of the period, but by the end tractors were employed in the majority of cases. It was during this period that the use of chemical fertilizers in horticulture began to replace the use of barnyard manure. Chemical fertilizers were used to a limited extent prior to 1918, but their wholesale use developed in horticulture during the 1918–1938 period.

The two systems of orchard management most generally employed are clean cultivation with cover crop, and grass sod mulch. During the early part of the century the clean cultivation and cover crop system was largely used in the commercial apple-growing regions. However, in the last fifteen to twenty years, fruit growers have become conscious of the limitations of the clean cultivation system, and there has been an increasing interest in soil management methods which will maintain the pro-

ductive capacity of orchard soil. The sod mulch system has gradually gained in favor because of the greater ease and economy with which organic matter may be maintained and because of the realization that severe soil erosion has occurred in clean-cultivated orchards situated on rolling land.

Very few radical changes in methods took place during the period 1938–1945 but mechanization became more widespread; spraying equipment became larger and more automatic and required fewer operators.

Since 1945 some of the most radical developments in horticultural

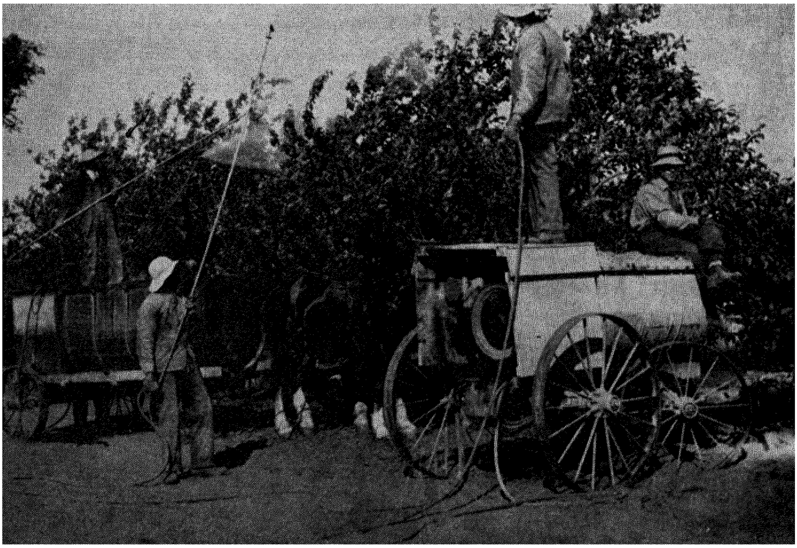

FIG. 7. The most modern method of spraying apple trees in use in 1918.

practices have been witnessed. The improvement in spraying equipment which started back in the 1920's took a very rapid stride with the introduction of the airblast sprayers operated by one man. This type of equipment, by cutting down manpower to one-third of that formerly employed and speeding up operations to three times the former speed, revolutionized what had been fast becoming an almost impossible task and so put a new outlook on the fruit business. This one advance may have spelled the doom of the small independent orchard (10–15 acres) for in its case the capital outlay necessary for the equipment is hardly warranted.

It was during this period that the change from the dilute to con-

centrate spray was introduced. These concentrate sprayers are presently more generally used in the west than in the east, but doubtless within a short period of time their general adoption in the east will follow the rapid improvements being made in the present equipment. Probably the most radical changes in other horticultural practices have been the introduction of hormone or growth-promoting compounds for the thinning of fruit and as aids to prevent the drop of fruit at harvest time, and the introduction of chemical weed control. Until recently, hand thinning, a laborious and costly practice, was the only method used in

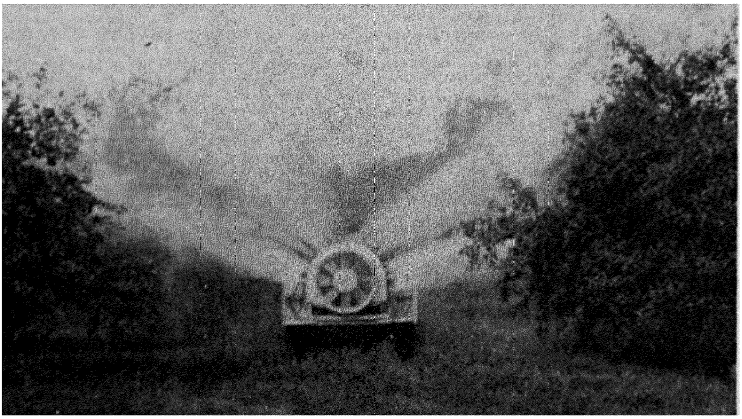

FIG. 8. The most modern method of spraying apple trees in use in 1952.

fruit production. In 1935, chemicals were first used as a method of removing a portion of the fruit. There are two types of chemicals used for thinning that can be applied by the conventional-type sprayers in the dilute form or in the "mist"-type sprayers in the concentrated form. At present the practice of chemical thinning is being used in all the commercial apple-growing regions.

Possibly no discovery has stimulated more interest in the field of horticulture than the finding of growth-regulating substances which would reduce the preharvest drop of apples just prior to and during harvest. Researches conducted in 1939 showed that two growth-regulating substances delayed the abscission phenomenon in apples. These findings suggested their use as a preharvest spray on apples. Since then, a large number of chemicals have been screened and more effective plant growth substances have been introduced. The materials are now very effective in reducing the preharvest drop and are widely used by all apple growers. The use of plant growth substances is now con-

sidered an excellent insurance on the season's investment in the apple crop.

The introduction of chemical weedicides, although of little interest to the fruit industry, has had widespread application in vegetable growing. Weed control in field carrots by the use of Stoddard solvent, preemergence treatment with chemicals for weed control in field peas, and postemergence treatment for corn, are practices which are quite widely adopted and which tend to cut down on one commodity that is becoming increasingly difficult to get—manpower.

3. New Varieties. In the early history of apple growing in Canada the varieties were largely those imported from the Old World and the United States. It is not surprising that, because of the severity of the climate in Canada, these varieties were not wholly adapted. Moreover, the early plantings were made of a large number of varieties with varying characteristics. As a result of the efforts of the plant breeders, a number of varieties have been selected which are better suited to Canadian conditions. The notable example is the McIntosh variety, which in 1951 constituted 30 per cent of the total apple production in Canada. The fruit lists of today are characterized by the few varieties now grown in contrast to some sixty varieties often grown in the commercial regions thirty years ago.

In vegetables it is the newer varieties introduced by the plant breeders that are making it possible for the food processing industries to move into the Prairie Provinces. There it is essential that the varieties of corn, tomatoes, and peas grown shall be adapted to the region—something which did not prevail around 1918.

At present the origination of more disease-resistant varieties is a main objective in most breeding programs. Tomatoes resistant to blight, potatoes resistant to scab and late blight, and peas resistant to root rot and pod spot are all under investigation in current projects.

4. Organic soils. Although 435,000 square miles of organic soil in Canada is situated where agriculture is climatically possible, only a very small portion had been utilized for horticultural crops by 1918. However, by 1938 about 10,000 acres of organic soil were being intensively cultivated for the production of vegetable crops in Ontario. Small areas were also in use in British Columbia, Quebec, and the Maritime Provinces. On most of these areas minor element deficiencies had occurred, and occasional serious loss was experienced from lack of boron, copper, and manganese. Up to this time only a very limited amount of experimental work with nutrition, varieties, and culture had been attempted, and growers were operating largely on advice from commercial companies and information contained in publications from the United States.

In 1934 a survey of the organic soils in southwestern Quebec was begun by the Quebec Soil Survey Committee, a joint provincial and dominion organization. As a result of the findings of this committee, detailed in a technical bulletin, "Organic Soils of Southwestern Quebec," the Canadian Government established a substation for vegetable production in 1936 on one of the larger areas of organic soil at Ste. Clothilde, Quebec. At this substation, research and experimental work was begun in 1937 and 1938 on nutritional requirements, water control, and cultural methods.

Between 1939 and 1945 an additional two or three thousand acres of organic soil was brought into cultivation for vegetables, and a distinct improvement in culture was effected. Owing to increased demand during these war years prices were high and production increased; however, considerable difficulty was experienced by growers in securing sufficient equipment, certain fertilizer ingredients, labor, and transportation for produce.

The past few years have been characterized by a substantial expansion of organic soil development as well as by improvement in production practices. In the Bradford area of Ontario about 3000 additional acres have been dyked and brought into cultivation. A large cold storage has been built, and a very efficient packaging and precooling plant has been put into operation. In addition the Ontario Government has established a substation on the area for the purpose of investigating the problems peculiar to that district. Production has also become more specialized, and the chief crops grown on the area are lettuce, onions, celery, potatoes, and carrots. On other organic soil areas in Ontario, celery and onions are the principal crops.

Growers on the organic soil areas of southwestern Quebec are steadily increasing the planting of potatoes, which in 1952 was approximately 3500 acres. This results from the increased demand for muckland potatoes when they are grown with a correct nutrient balance. The production of head lettuce, onions, carrots, and celery has remained about constant during the past six years. However, there has been an increase in production of certain specialized crops for processing, such as broccoli and spinach. Drainage outlets for 40,000 acres have been provided by the Quebec Government and the area is now ready for a substantial increase in development.

Suitable methods for irrigation and the water requirements for the principal crops have been determined. The nutrient requirements of the most of the vegetable crops when grown on organic soils have been calibrated,.and fertilizer recommendations for the district made available. A rather intensive study of minor element requirements has been

made, and the need of boron, manganese, copper, and zinc established, in part or whole, for various crops. Weed control, which is one of the major problems on organic soil, has been worked on steadily, and efficient and economic weed control has been established for several crops on these soils.

Precooling of vegetables has been a major project, and an efficient and satisfactory type of hydrocooler has been developed.

At present the most important problem with organic soils appears to be the accumulations of mineral nutrients which arise from excessive applications of fertilizer and which disturb the soil nutrient balance. Accumulated potash ties up magnesium, inducing deficiency and loss of crop. Weed control is still a problem, and more suitable varieties of many kinds of vegetables are urgently required. Also provision will have to be made for the processing of surplus production and more cold storage, and finally, marketing methods should be improved.

5. Greenhouse crops. Although there are not any reliable statistics on the greenhouse industry in Canada, it has reached sizeable proportions. It is estimated that at present some 12 million square feet of glass is devoted to the floral industry and some 8 million feet to the vegetable industry, with an unknown area occupied by growers who deal in annual bedding plants.

In the cold climate prevailing in most of Canada, cost of fuel is a tremendous factor in the economics of greenhouse production. This, coupled with the availability of southern-grown produce during the winter months, has influenced the kinds of crops to be grown. Thus, greenhouse-grown lettuce in winter, which at one time was common, is now a rarity. Competition from Californian outdoor-grown material has made this crop generally unprofitable.

In contrast to this the floral end of this industry has, by adoption of more modern practices, been able to expand. Some of the newer techniques adopted are: improved soil sterilization; automatic or semiautomatic watering; more efficient insecticides and fungicides; aerosol dispersion for insecticides—a labor-saving device in spray application; and application of modern knowledge of photoperiod requirements of plants.

6. The future. The pattern of the foreseeable future would appear to be set by the developments of the last ten years. With improved and more adaptable varieties, the commercial growing of horticultural crops will be expanded to newer regions.

In the older parts of central Canada, where industrial development is making rapid strides, it is predictable that horticulture may assume a decreasing importance in the over-all economy. It may even be that

the growing of such tender fruits as peaches, cherries, and grapes will become less important in eastern Canada, and that this region will be obliged to look to British Columbia and the southern United States for the bulk of these crops.

Mechanization will undoubtedly continue to increase. Already appearing are sweep rakes for gathering prunings and hydraulic pruning shears and orchard giraffes designed to eliminate the use of ladders in pruning. Of more recent origin is the vacuum picking equipment for the harvesting of tree fruits. Many of these machines are still in the development stage, but they all indicate the trend: larger operations, more mechanization, less manpower per acre.

VI. Tobacco

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1. *Statistics*

In Canada, there are grown five main types of tobacco, namely, flue-cured, burley, cigar, dark, and pipe tobaccos. The principal tobacco-growing regions in Canada are located in the provinces of Ontario and Quebec. The "old" tobacco belt in Ontario is mainly in Essex and Kent counties; the "new" belt in that province is located in the counties of Norfolk, Elgin, Middlesex, Oxford, and Brant adjoining Lake Erie. Smaller areas are located in Durham and Simcoe counties. In the province of Quebec, the major tobacco-growing areas are located north of Montreal in Montcalm and Joliette counties. Another area is found along the Yamaska Valley in and around the county of Rouville. Small areas are planted to tobacco in British Columbia. The total acreage of all types of tobacco in Canada was 13,403 valued at $4,967,000 in 1918; 83,575 valued at $20,269,000 in 1938; 93,277 valued at $30,640,000 in 1945; and 119,000 valued at an estimated $66,213,000 in 1951. The acreage of bright or flue-cured tobacco was 63,530 in 1938; 77,200 in 1945; and 111,000 in 1951. The total farm value of the flue-cured crop rose from $2,115,000 in 1927 to a record of $63,729,000 in 1951. This type, the most important grown in Canada, is an important crop in southwestern Ontario and as well as in a limited area in the province of Quebec.

In 1927, of a total planted of 44,028 acres for all tobacco types, 20,510 acres were planted to burley tobacco, the principal type grown. It was grown entirely in Essex and Kent counties in Ontario. At that time, only 7,570 acres, all in Ontario, were planted to flue-cured tobacco;

5,806 acres, all in Quebec, to cigar tobacco; 5,750 acres, all in Ontario, to the dark type; and 4,392 acres, all in Quebec, to pipe tobacco. By 1938, the priming method of harvesting flue-cured tobacco was in general use, and this type of tobacco became the principal one grown. In that year, out of the total tobacco planting in Canada of 83,575 acres, 63,530 were flue-cured; 9,215 burley; 5,065 cigar; 3,000 dark; and 2,765

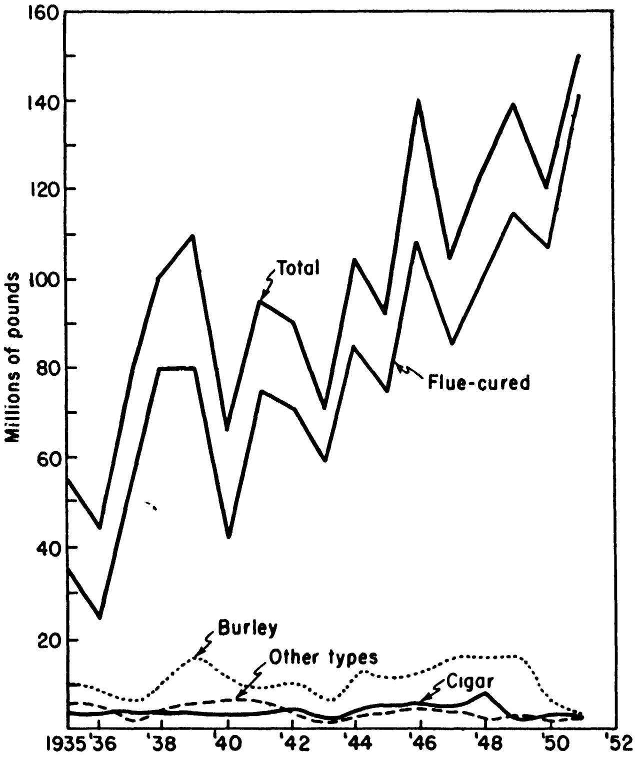

FIG. 9. Production of leaf tobacco, 1935–1952.

pipe tobacco. The total farm value of the crop had increased to $20,-269,700.

By 1945, the flue-cured type had assumed even greater importance; out of a total planted area in Canada of 93,277 acres for all types, 77,200 acres were planted to flue-cured tobacco. By that year, 9,442 acres were planted to burley; 3,093 acres, to cigar tobacco; 2,188 acres, to pipe tobacco; and 1,354 acres, to dark tobacco. The total farm value of the tobacco crop was $30,620,000.

By 1951, about 98 per cent of the leaf tobacco used by Canadian to-

bacco manufacturers was produced in Canada. The acreage of flue-cured tobacco had increased to 111,296, out of a planted area of 118,969 acres for all types of tobacco. The acreage was reduced to 2,478, 3,000, 1,225, and 969 respectively for burley, cigar, pipe, and dark tobacco. The total farm value of the crop had increased to $66,212,907, of which the flue-cured type accounted for $63,728,861. That year, 140,022,947 pounds

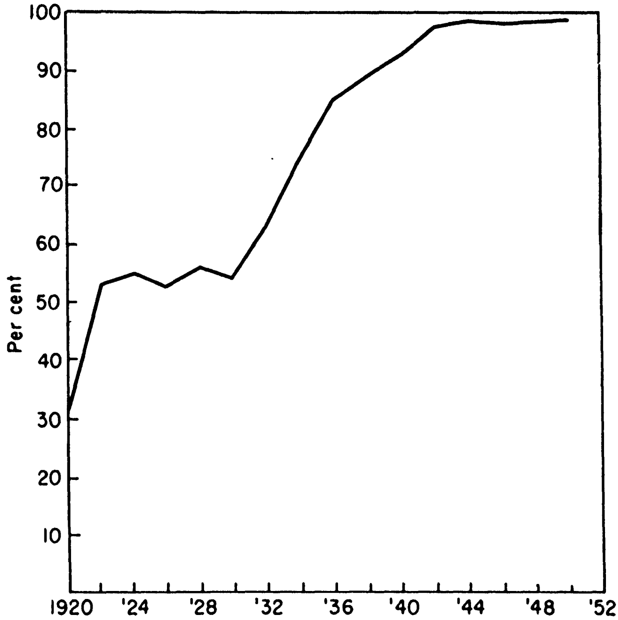

FIG. 10. Per cent of domestic leaf used by Canadian manufacturers, 1920–1952.

of flue-cured tobacco were produced in Ontario, 3.8 million pounds in Quebec, and 183,908 pounds in British Columbia. Including all types, Ontario produced approximately 145 million pounds of tobacco, Quebec produced 8.6 million pounds, and British Columbia produced 185,908 pounds.

2. *Breeding*

The early improvements in the yield and quality of tobacco in Canada may be attributed to the introduction of foreign varieties and to the selection and purification of those adapted to Canadian conditions. Until the Experimental Farms Service was established, tobacco farmers usually collected their own seed from open-pollinated field plants, resulting in a very mixed, uneven crop which produced a low-quality product. In order to overcome this fault, seed samples were collected by Experi-

mental Farms workers from both Canadian tobacco growers and foreign sources and grown in small plots where the plants were carefully examined for purity and evaluated as to quality. Selections were made on this basis, and strains true to type were developed; this increased materially the acreage, production, and value of the tobacco during the period 1918–1938. As this period of development progressed, increasing attention was paid to the production of new varieties of tobacco, particularly those of the burley, cigar, and flue-cured types. In the case of burley, black rootrot became so serious a disease that breeding of rootrot-resistant varieties became a major project. An extensive hybridization program was initiated, resulting in the production of several new varieties. In 1935, the HARROW VELVET burley variety was produced as a black-rootrot–resistant variety of a new cigarette leaf type. Not only is it resistant to this disease but in a four-year test on soil not infested with the black-root organism, it outyielded seven other commonly grown varieties by 340 pounds per acre and at the same time graded 2 cents per pound higher. In the same year, the cigar variety RESISTANT HAVANA 211 was imported and tested in Canada. Several selections were made and, in later years, were released to growers in Quebec.

During the period 1939–1945, considerable progress was made in the flue-cured tobacco breeding work. This was influenced primarily by a change from the stalk-cut method of harvesting to the priming method which occurred around 1930. Many new varieties and selections, such as WHITE MAMMOTH 61, YELLOW MAMMOTH 58, BONANZA 68 and DUQUESNE 72, were introduced by the tobacco research workers, and those most adapted to Canadian conditions were released to the flue-cured growers. The resultant expansion in the flue-cured tobacco acreage was so rapid that, by 1945, approximately 80,000 acres were being grown. As products of the burley breeding program, the varieties HARONOVA and HARMONY were introduced as root-rot-resistant strains of the cigarette type of burley tobacco.

In the period 1946–1951, the breeding program was intensified, and studies of mosaic resistance, earliness in maturity, and leaf shapes were well advanced. In 1948, the flue-cured variety DELCREST was introduced and because of its superior quality, including high resistance to black rootrot, its use spread so rapidly that by 1951 two-thirds of the flue-cured acreage was being planted to this variety. In 1950, a new burley variety, BRIARVET, was released to the burley growers. It is estimated that the three varieties released between 1939–1951 produced over 35 per cent of the burley crop, and that HARROW VELVET produced a further 50 per cent of the burley tobacco production.

Several breeding problems are being studied intensively at the present

time; this research may improve the yield and quality in the future. Tobacco mosaic causes considerable loss each year to the tobacco grower; similarly, early frosts in the fall result in damaged leaf. Breeding projects to overcome both these hazards are being conducted. The production of first-generation hybrids showing hybrid vigor is also being investigated and tested. New types of resistance to the common diseases are being studied in order to increase the disease resistance of our accepted varieties.

3. *Fertilizers and Soil Amendments*

When World War I ended, the use of chemical fertilizers was a well-established practice with most tobacco farmers. Since 1918, soils and fertilizers research in connection with tobacco has been directed towards establishing ideal nutrition of the plants, namely, an adequate and continuous available supply of all essential elements to promote rapid, maximum growth, with a rapid decline in this supply, particularly of the available nitrogen supply, as the crop approaches maturity. Maximum yields and superior quality have been considered as the dominant objectives at all times.

Probably the most outstanding development in this field during the period 1918–1938 was the formulation, by a special advisory committee, of tobacco fertilizer recommendations based on an annual review of experimental results. Farmers were thus assured by law that commercial fertilizer mixtures were manufactured according to the latest recommendations. The former rate of application of several hundredweights per acre was increased to about 1000 pounds of fertilizer per acre. The practice of liming was discontinued to reduce the incidence of black rootrot development in susceptible varieties. The source of potash was restricted to the sulfate salt instead of the chloride, as the latter was considered detrimental to tobacco smoking quality. Experiments also showed that less nitrogen and more potassium in fertilizer mixtures greatly improved the quality and that more phosphorus promoted earlier ripening.

Consequently, for flue-cured tobacco, the fertilizer formula recommended and used on light sandy soils was changed from 3-8-4 to 3-10-8 before 1930, and to 2-10-8 by 1936. For burley and dark tobaccos, the formula 4-8-6 was changed to 4-8-10 on the lighter sandy loam soils, and the formula 2-12-6, to 2-12-10 on the heavier clay loam soils. For cigar and pipe tobaccos, the 5-8-7 and the 5-8-10 formulas were introduced for use on sandy loam soils. A manure supplement was applied at the rate of not more than 5 tons per acre, for flue-cured tobacco, and 10 to 20 tons per acre, for other tobaccos.

During the war period, 1939–1945, crop rotation systems became rec-

ognized as more important in order to avoid the development of soil-borne diseases and nutrient deficiencies. The higher potash fertilizer mixture, 2-12-10, was introduced for soils low in potash to improve the quality of flue-cured tobacco crops. There was thus prevented potash-deficiency in plants caused by an excessive supply of available nitrogen in soils that might have an adequate supply of potash for a slower rate of growth. Later in the war years, the use by tobacco growers of small grain and legume rotation crops or of too much barnyard manure and the restricted use of potash were frequent causes of potash deficiency and reduced quality of flue-cured leaf.

Since 1946, the use of expensive organic materials, such as cottonseed meal and blood meal has been discontinued, and ground dolomitic limestone has become a necessary adjunct to supply magnesium and calcium in commercial NPK mixtures. The two-year rotation, rye-tobacco, has proved to be satisfactory and popular with flue-cured tobacco growers. The practice of discing under a mature crop of rye straw with nitrogen fertilizer in August and a green manure crop of rye the following May, preceding tobacco, has largely replaced the use of barnyard manure as a source of organic matter and extra plant food in flue-cured tobacco soils. Most fertilizer is now applied in bands, viz., 4 inches on each side of the row and 4 inches deep, by use of the fertilizer attachment on the planting machine, replacing the former row placement and broadcasting methods.

In 1951, fertilizer application on tobacco crops in Canada exceeded 120 million pounds. In less than twenty years, areas of sandy soils, some of which were of little agricultural value, were transformed into the most prosperous farming districts in Canada, where valuable food crops, as well as tobacco, are now grown profitably. Future fertilization trends, based on information already well-advanced in the research stage, promise to add further improvements in both quality and yield of tobacco. These trends are: more potash and less sulfate in fertilizers; improved placement methods, viz., the best time and quantity in respect to side-dressing part of the NPK fertilizer application, and supplementary applications of individual nutrients including minor elements; and finally, the judicious use of lime, new soil conditioners or organic matter sources, and the fertilizing of other crops grown in rotation with tobacco.

Future expansion of the tobacco industry in Canada is dependent upon an increase in the Canadian population and further development in export markets. The demand for flue-cured tobacco will likely continue to grow for some few years, but no appreciable increase in the production of other types is anticipated at this time.

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Soil Management for Conservation and Productivity

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CONTENTS

I. Introduction

A favorable supply of nutrients in the soil does not insure good crop growth. Knowledge of the amount and availability of nutrients is commonly taken as an index of fertility. Such information alone does not give a reliable indication of plant growth and yield to be expected. Plants require nutrients, water, and air in the soil for survival. Beyond mere survival, the balance of these factors in the soil has a bearing on the vigor and extent of growth and on the level of productivity of crop plants. If insufficient moisture is available to plants from the soil, nutrient uptake is limited and growth restricted. If an excessive amount of water is present, air is excluded from the soil pores, and plants are unable to carry on normal respiration and growth functions. Crop plants require a favorable air-water balance in the soil for normal root growth and distribution. Thus, any limitation of oxygen supply may further reduce plant growth by limiting the volume of soil occupied by the root system. Any such restriction of the root zone acts to further limit the quantity of nutrients and water available to the growing plant.

The air-water relationships of the soil are necessarily dependent on the physical condition or structure of the soil. According to Baver (1948, p. 126): "Soil structure is usually defined as the arrangement of the soil particles. This concept, however, requires a clear understanding of

the word 'particles'. As far as structure is concerned, soil particles refer not only to the individual mechanical elements, such as sand, silt and clay, but also to the aggregates or structural elements, which have been formed by the aggregation of smaller mechanical fractions. The word, 'particle,' therefore, refers to any unit which is a part of the makeup of the soil, irrespective of its being a primary (sand, silt or clay fraction) or a secondary (aggregate) particle. Consequently, the structure of a soil implies an arrangement of these primary and secondary particles into a certain structural pattern.'' More specifically, the air-water relationships of the soil are dependent on the volume and nature of the pore space present. The water-holding capacity of a soil is dependent on the smaller pores, whereas the rates of water absorption at the surface and of internal drainage depend on the relatively larger pores. Aeration, necessarily, is dependent on pore space and tends to vary more or less directly with the volume of larger pores. Certain general requirements concerning desirable physical conditions of the soil can thus be established. The volume of pore space must be sufficiently great to permit favorable air-water relationships. When water is present in amounts favorable for vigorous plant growth, sufficient volume of pore space must remain unfilled with water to provide air to meet the oxygen requirements of plant roots. In addition to some minimum volume of total porosity, the size distribution of soil pores has an important bearing on the maintenance of favorable air-water relationships. As indicated earlier, the moisture-holding capacity of the soil is dependent on the smaller pores, usually identified as capillary pore space. Drainage of water during periods of excessive rates and amounts of applications occurs by means of the larger, noncapillary pores. These larger pores provide air space. During periods of heavy precipitation or irrigation applications, it is essential that these larger pore spaces drain readily if an adequate oxygen supply is to be maintained.

II. Factors Influencing Soil Structure

1. *Cultivation Effects*

Deterioration of soil structure commonly occurs as a result of or in connection with cultivation operations. When virgin soils are first brought under cultivation, the over-all physical condition of such soils is usually favorable for plant growth. With adequate moisture and nutrients, highly productive crop growth can be expected. Such soils ordinarily are loose, friable, and easily worked. Water is absorbed rapidly at the surface and moves readily into the profile. As a result of the ready

absorption, run-off and resulting erosion losses are comparatively low. Individual soil particles tend to be bound into stable aggregates. Water falling on the soil surface does not bring about dispersion of the aggregates, with resulting crust formation. Individual soil particles held in aggregates do not move downward to clog soil pores and thus limit water and air movement. Favorable air-water relationships encourage deep root penetration and thus contribute to drought resistance in the crops grown.

As cultivation of these soils continues, there is a gradual deterioration of structural qualities. The rate and, in a large measure, the extent of such structural deterioration varies with the intensity of cultivation and the cropping system followed. Numerous examples have been reported showing a decided reduction in organic matter and nitrogen as a result of cultivation operations. In addition to other effects, losses of organic matter are ordinarily accompanied by decreases in the extent of aggregation. Jenny (1933) reports a 38 per cent decrease in organic matter content of Putnam silt loam in Missouri after sixty years of cultivation. A 33 per cent decrease in available bases and a corresponding decrease in degree of aggregation occurred during the same period. Other soils showed similar reductions in organic matter content and in aggregation under conditions of cultivation.

Bradfield (1936) has reported a total porosity of 60.3 per cent and a yield of 80 bushels per acre of corn from the first crop following sod. An immediately adjacent area that had been under cultivation showed a porosity value of 50.5 per cent and a corn yield of 20 bushels per acre. Porosity of a clay soil was shown to have been decreased by as much as 18 per cent during forty years of cultivation.

Anderson and Browning (1949) show data on physical and chemical changes resulting from cultivation of six Iowa soils. Physical properties investigated included permeability, aeration porosity, volume weight, and degree of aggregation. In this report, effects of cultivation on permeability of the soils were variable. In regard to other physical properties, it is shown that cultivation has resulted in decreased air-porosity, considerably reduced aggregation, and an increase in volume weight. Data on changes in nitrogen content indicate a substantial reduction in organic matter content in all cases as a result of cultivation operations.

Retzer and Russell (1941) show a general deterioration of soil physical conditions as a result of cultivation operations. Marked changes in physical condition of a clay soil under cultivation are reported by Page and Willard (1946). The upper 3 feet of the profile, under virgin conditions, weighed 70.8 pounds per cubic foot. Following cultivation for an extended period, this value increased to 86.5 pounds. In addition to

this change in bulk density, the porosity of the soil decreased from 57.3 per cent to 47.6 per cent. It is interesting to note that these changes in structure were not limited to the plowed layer but extended to a depth of 3 feet in the profile. The report emphasizes the effect of these changes in physical properties of the soil on air and water capacity and on drainage conditions within the profile.

The preceding discussion indicates that cultivation operations, in general, tend to reduce the extent of aggregation, reduce the volume of pore space, and increase the weight of soil per unit volume. The content of organic matter is ordinarily reduced as these physical changes occur. The data indicate that the cultivation process, by loosening the soil and temporarily increasing the volume of air space, leads to more rapid decomposition of organic matter than occurs under sod cover. As the organic materials are decomposed, soil aggregates tend to become dispersed. Breakdown of aggregates permits closer packing of soil particles, with the accompanying decrease in porosity and increase in density cited above.

2. *Mechanical Compaction in Cultivation*

In addition to the above factors, the direct effect of machine operation on soil compaction should be noted. During the past few decades the use of horse-drawn field equipment has largely given way to motor-driven equipment. As the size and power of tractors increased, larger and heavier cultivating and harvesting equipment came into use. Such equipment has not only contributed to soil structure deterioration through more vigorous and more frequent cultivation but has also resulted in serious compaction resulting directly from wheel traffic.

The writer and his associates found wide differences in the bulk density and porosity of Sassafras loam depending on the intensity of wheel traffic. An area in potato production showed an average bulk density of 1.33 for samples taken in the plant row. Samples from row middles, which had normal tractor and sprayer traffic, averaged 1.46 in bulk density. Air-filled pore space was 24.2 per cent in the row and 15.9 per cent in the middle.

Jamison *et al.* (1950) in soil bin tests found that soil compaction from pneumatic tractor tires varied with the soil moisture content and with the initial looseness of the soil. On dry, compact soil little increase in bulk density occurred under the tire action. On loose, moist soil, more or less comparable to seedbed conditions, bulk density was increased from 0.94 to as much as 1.39 by the movement and pressure of the tractor tire.

Free *et al.* (1947) found that soil compaction, under a given set of

conditions, was reduced as the organic matter content of the soil increased. Parker and Jenny (1945) emphasize the importance of organic matter additions and the absence of cultivation for maintenance of soil structural conditions. Either cover crops or manure additions greatly increased water infiltration in orchard soils. Tractor traffic and heavy disking brought about significant increases in volume weight and reductions in soil porosity. Elimination of cultivation and regular use of cover crops reduced resistance to penetration, reduced core weights, and brought about marked improvement in the rate and amount of water infiltration.

Weaver (1950) and Weaver and Jamison (1951) found that maximum compaction of Cecil clay and Davidson loam under implement traffic occurred at a moisture content near the optimum for plowing. It is emphasized that tractor and other heavy machinery operations should be performed at moisture contents as low as practicable for the work to be done.

3. *Organic Matter Effects*

It has long been recognized that organic matter content is related to physical properties of the soil. A high level of aggregation or granulation in the soil is usually associated with plentiful supplies of good quality organic matter. Further evidence of the granulating effect of organic matter occurs in the fact that organic materials must be made soluble in order to obtain dispersion of soils for mechanical analyses.

It has been shown by Baver (1935) that a significant correlation exists between the percentage of aggregates larger than 0.05 mm. and the carbon content of a wide variety of soils. A higher correlation coefficient was found for aggregates larger than 0.1 mm., indicating that organic matter tends to favor the formation of relatively larger aggregates. When various soils were grouped on the basis of clay content, it was noted that the aggregating effect of organic matter was greater in the soils containing the smaller amounts of clay. A high correlation was found between organic matter content and aggregation in soils containing less than 25 per cent clay. A significant but much lower correlation was found for soils containing higher amounts of clay. The relatively greater effectiveness of organic matter in promoting aggregation in soils of low clay content is of interest later in this report, where data from a loamy sand soil are discussed in some detail.

Myers (1937) reports that colloidal organic matter is more effective than clay in the formation of stable aggregates with fine quartz sand and orthoclase particles. His results emphasize the importance of dehydration in the process of stable aggregate formation. The effectiveness of

organic matter additions in bringing about the aggregation of silt and clay particles has been reported by Kolodny and Neal (1941). Manure applications and winter cover-crop practices were shown to increase aggregation of fine particles in the soil. Richards *et al.* (1948) in a subsequent report showed similar results. In addition, it was pointed out that the aggregating effect of the treatments persisted to a greater or less extent for a six-year period following cessation of the treatments.

McCalla (1945) suggests that the quantity of organic matter, within reasonable limits, is less important than the quality in producing aggregate stability. This report indicates that structural stability is temporary, lasting only as long as the stabilizing decomposition products continue to exist in the soil. These data appear to support the view, expressed elsewhere in this discussion, that continuing aggregation and structural stability in cultivated soils require regular additions of organic matter.

Uhland (1949) has shown increases in percolation rates and in volume of pores drained at a given tension following crops of kudzu and alfalfa. On a desurfaced Shelby silt loam, the bulk density of exposed surface material was reduced from 1.31 to 1.00 at the end of twelve years in a grass-legume sod mixture. Sassafras loam under continuous cultivation in potatoes showed significant increases in degree of aggregation with annual manure applications, as reported by Klute and Jacob (1949). Bulk density values decreased in all cases at the higher manure applications as compared with unmanured areas.

Lutz *et al.* (1946) report an interesting case of differences between cultivated crops in regard to effects on structural properties of the soil. It seems reasonable to expect that the growth of cultivated crops would tend to bring about improvement in soil structure similar to that effected by grass-legume mixtures and other noncultivated plant growth. With cultivated crops, however, such a tendency for structural improvement is largely nullified by the cultivation operations which accompany growth of the crop. In the above report it is shown that soil porosity was the same under a cotton-corn system without cover crop and a cotton-peanuts system with winter cover. This appears to support the data of Martin (1942) indicating that corn stover is a particularly favorable type of organic material for improvement of soil structural conditions.

Uhland (1947) emphasizes the effect of grass and legume crops on the stability of aggregation in the soil. Data are reported in terms of the number of drops of water falling 30 cm. required to disperse soil aggregates of a selected size formed under different cropping systems. It is shown that an average of 6.2 drops dispersed the aggregates of a soil that had been in continuous corn and 7.5 drops dispersed the aggre-

gates found in an area that had been under clean fallow for thirteen years. In contrast to this condition of relatively unstable aggregation, it took 41.2 drops to disperse aggregates from second-year meadow and 40.2 for samples from a thirteen-year old alfalfa treatment. No significant difference in the water-holding capacity of a fine sandy loam resulted from the use of winter cover crops, as reported by McVickar, *et al.* (1946).

Alderfer and Merkle (1941a) found that structural breakdown in the soil varied directly with the intensity of cultivation. Soil areas under a corn, oats, wheat, clover rotation showed deterioration in physical conditions as compared with areas under sod. In turn, areas under continuous cultivation were in less favorable structural condition than were the areas in rotation. The stability of aggregates was found to be positively correlated with the organic matter content of the soil. Bulk density values showed an inverse relationship to aggregate stability and organic matter content.

Woodruff (1939) reports that cultivated soils receiving regular manure applications or soils cropped to a rotation including the regular use of grass-legume mixtures, were found to possess a higher state of aggregation than that in untreated soils cropped continuously. He further points out that the physical properties of a cultivated soil imparted by organic matter may be more closely associated with past crop history and soil treatments than with the properties of the virgin profile.

Metzger and Hide (1938) point out the improvement in soil aggregation resulting from two years growth of alfalfa and of sweet clover under field conditions. Hide and Metzger (1939) found little or no improvement in soil aggregation resulting from the growth of bluegrass for a four-month period under greenhouse conditions. When finely ground wheat straw or alfalfa was mixed with the soil, the improvement in aggregation was similar to that occurring under growth of the crop.

Waksman and Martin (1939) found that ground alfalfa or straw increased the degree of aggregation of a Coastal Plain soil. The alfalfa produced an earlier and greater effect than did the straw. This result appears to be related to the relatively more rapid rate of decomposition of the alfalfa. Peele (1940) has shown the positive relationship between microbial activity and the resulting rate of organic matter decomposition and the rate and extent of soil aggregate formation.

It is not intended, in the foregoing section, to imply that organic matter content and activity in the soil is the only factor of importance bearing on the formation of stable aggregates. The development and maintenance of stable granulation of soil particles obviously is influenced by wetting and drying, freezing and thawing, clay content, numerous

chemical reactions, and a variety of other factors. The operation of these factors, however, tends to be fixed by the nature and location of the soil under consideration. Organic matter content is one of the few factors, and possibly the only major factor, influencing aggregate formation and stabilization which lends itself to systematic manipulation in the soil management program. Cropping systems can be designed to provide regular additions of organic matter in cultivated soils and thus permit continuing maintenance of favorable levels of particle aggregation.

III. Soil Management for Structure Maintenance

1. *General*

It is common knowledge that soils generally possess favorable physical properties when first brought under cultivation from a virgin condition. Land operators who have cleared timberland or plowed virgin sod are well aware of this fact. As cultivation continues on such areas, the soil becomes less open and friable. Organic matter content is reduced with a resulting tendency for the breakdown of soil aggregates. As dispersion of the aggregates progresses, the soil particles become more closely packed together, bulk density increases, and the volume of pore space is reduced. Aggregate dispersion commonly proceeds more rapidly at the soil surface than at levels below the surface. This area, under cultivation conditions, is exposed to the beating action of raindrops in addition to exposure to other forces of structural decline. Difficulties with crust formation following rainstorms tend to develop as dispersion of aggregates in the surface layer continues. This condition often introduces problems of securing satisfactory seed germination and usually reduces the rate of water absorption, thus increasing runoff losses.

There are many examples in the literature showing the beneficial effects of permanent vegetation and of the absence of cultivation on soil physical conditions. The influence of grass-legume mixtures in promoting aggregation of the Hagerstown soil is reported by Alderfer (1950). The value of sod in rotation with cultivated crops for the maintenance of soil structure is emphasized. Wilson *et al.* (1947) report that the percentage of aggregates larger than 2.0 mm. under crops studied was continuous bluegrass > rotation meadow > rotation corn > continuous corn. With the methods of measurement used, the aggregates formed under rotation meadow and rotation corn were less stable than those under continuous bluegrass. With a four-year rotation of corn, wheat, clover, and grass, Elson (1943) found that the soil under wheat had the same percentage of macroaggregates (larger than 1.0 mm.) as

that under corn. Soil under clover showed a 10.3 per cent increase in aggregation over wheat areas, and the grass treatment brought about a 9.1 per cent increase over clover.

Alderfer and Merkle (1941b) have reported studies relating to the structural stability and permeability of native forest soils compared with cultivated areas of the same soil types. In general, it is shown that soils under forest or under continuous bluegrass are relatively high in permeability and organic matter content, with relatively low values for volume weight. Soils under rotation of cultivated crops and grass-legume mixtures show intermediate values, whereas soils under continuous cultivation show comparatively low values for permeability, reduced organic matter content, and relatively high values for volume weight. It is pointed out that land under bluegrass or other sod-forming grasses, if not subjected to compaction, may develop a degree of granulation equal to or better than that found under forest conditions. Heavily trampled and pastured sod, on the other hand, may become nearly as compact and impervious as land used for intertilled crops. This report emphasizes the fact that when soils are brought under cultivation there is ordinarily a slow but significant breakdown of structure. This process is greatest and most rapid when intensively tilled row crops dominate the cropping system.

The deleterious effect of continuous cultivation on soil structure is emphasized by Rynasiewicz (1945). Soil organic matter content and degree of aggregation under different cropping systems varied in the order of: onions and two years of mangels $<$ onions and buckwheat $<$ onions and corn $<$ onions and redtop $<$ permanent grass sod. Positive correlation between degree of aggregation and onion yield is shown.

In general, the effect of tillage is to destroy soil structure through the breakdown of aggregates and granules. The extent of the destructive effect varies widely with different soil types. Considerable variation may occur within a given soil type depending on moisture conditions at the time of tillage and on the type and severity of cultivation operation carried out.

Growing crops influence the structure of the soil both directly and indirectly. Most of the foregoing examples deal principally with the indirect effects. These, in general, may be considered as the changes in aggregation and porosity of the soil resulting from organic matter produced by plant growth. Certain very real direct effects occur, although it often is difficult and may in some cases be impossible to evaluate them separately from the influence of added organic matter. The two principal direct effects of vegetation on soil structure are due to the canopy

protection afforded by leaves and stems against raindrop impact and to the influence of root activity on soil physical conditions.

The effectiveness of different crops at various growth stages in intercepting rainfall has been shown by Haynes (1938). Ellison (1944, 1948) has emphasized the influence of raindrop impact on bare soil in dispersing soil aggregates, in compacting the surface layer, and in initiating runoff and erosion. Ekern (1950) reports on a study concerning the energy relationships of drop impact comparable to that found in natural rainfall. He reports that this is a mechanism of sufficient quantitative importance to be responsible for much of the accelerated sheet erosion from cultivated soils.

Baver (1948, p. 182) quotes data reported by Wollny in 1874 showing that rye, peas, and vetch protected the soil to such an extent that the noncapillary porosity of a calcareous sandy soil was 34–53 per cent higher than that of an adjacent unprotected soil. This report indicates that canopy protection is particularly effective in maintaining the content of large pores in the soil. The deterioration of structure resulting from raindrop impact was evident more as a decrease in the volume and number of large pores than as a decrease in total porosity. An example given shows the total porosity of an unprotected soil to be about 6 per cent less than that of a soil protected by vegetation. Noncapillary porosity, however, was reduced by 31 per cent on the unprotected soil area.

Structure deterioration and compaction of the soil surface is a matter of considerable importance from the standpoints of both crop production and water conservation. Compacted surface layers, resulting in crust formation, may interfere seriously with seed germination and successful establishment of seedling stands. In addition, the reduced rate of water absorption through the compacted layer often results in excessive rates and amounts of surface runoff, regardless of the structural and water-transmitting properties of the soil immediately below the surface layer. Protection of the soil surface against aggregate destruction is one of several factors responsible for the effectiveness of grass-legume mixtures and other close-growing vegetation in both structure maintenance and conservation of soil and water.

It is difficult, if possible at all, to distinguish between direct and indirect influences of root growth on physical conditions of the soil. It seems obvious that organic matter introduced at various soil depths through root growth would, upon eventual decomposition, exert a favorable influence on soil structure. This, in fact, is the only practicable means of introducing fresh organic materials at levels below plow depth. In addition, the pressures exerted by growing roots, the binding action of fine fibrous roots, and the wetting and drying cycles resulting from water

usage and replenishment would all be expected to contribute to improved aggregation and general structural properties of the soil.

2. *Crop Rotations*

It has been pointed out in the foregoing sections that soil organic matter is one of the important factors influencing soil structural conditions. It is also indicated that cultivation tends to bring about deterioration of structure. This latter effect appears to be the result of increased rates of organic matter decomposition, reduced amounts of vegetative residues returned to the soil, exposure of the soil surface to rainfall action, and compaction of the soil by cultivation machinery. Doubtless other factors are involved.

Despite the unfavorable effects of cultivation on soil structure, there seems no doubt that cultivation will continue to be necessary at some level of intensity in many agricultural enterprises. The problem, then, is to devise crop and soil management systems which permit the production of cultivated crops and, at the same time, provide sufficient organic matter additions to maintain favorable soil structural conditions. There is little possibility and, for that matter, no particular need to maintain the organic matter level in cultivated soils at levels found commonly in virgin soils. The real need is for a cropping system which provides additions of good-quality organic material to the soil at regular intervals. It is then desirable, from the standpoint of soil structure maintenance, that decomposition of the organic material proceed at a reasonably rapid rate. Organic matter decomposition, in addition to the beneficial effects resulting from nutrient release, is desirable and necessary under average conditions in order to maintain the soil in a well-aggregated condition which is resistant to erosion and in order to maintain a productive condition. The accumulation of a large amount of organic material that was highly resistant to decomposition would not necessarily contribute to good physical condition of the soil or to soil productivity. The desirable condition, as pointed out, is one where a system of crop and soil management is so arranged that additions of good-quality organic material are made at regular intervals. The normal decomposition processes that contribute to good physical condition of the soil can then proceed without danger of the eventual exhaustion of soil organic supply.

A practical and time-proved method of maintaining favorable physical conditions in cultivated soils is through the rotation of cultivated crops with grass-legume sods or other close-growing, noncultivated crops. Bailey and Nixon (1948) state that "the ideal rotation is one that achieves complete harmony between the farmer's demand for cultivated crops and the needs of the land for protection." It is pointed out that

a good rotation is one that includes enough grass and legumes to reduce soil and water losses, reduce leaching of plant nutrients, maintain organic matter supply, improve soil structure, and increase acre yields of cultivated crops in the rotation. This rather large order seems entirely within the realm of possibility. Effects of grass-legume sod in rotation on organic matter and soil structure have been shown. The influence of such rotation systems on soil and water losses and on yields of cultivated crops is discussed below.

IV. Influence of Rotations on Conservation and Productivity

The influence of crop rotations and resulting differences in physical condition of the soil on productivity and on soil and water losses is closely interrelated. The improvement in aggregation and porosity of the soil resulting from the sod rotation would be expected to increase the rate and amount of water absorption during rainfall periods. This, in turn, would decrease runoff and accompanying erosion and provide more favorable moisture conditions in the soil. Decreases in the amount of erosion would reduce the extent of nutrient loss from the soil. Whitson and Dunnewald (1916) reported that erosion sediment contained 3 times the concentration of nitrogen and 2 times as much phosphorus as was contained in the soil from which the sediment came. Miller and Krusekopf (1932) report similar data emphasizing the selective nature of the erosion process. The writer (1944) showed that eroded material from a loamy sand soil contained about 5 times as much organic matter and nitrogen, 3.1 times as much P_2O_5, and 1.4 times as much K_2O as compared with the concentration of these materials in the surface soil. The soil contained about 16 per cent silt and clay, whereas the eroded material contained 58 per cent of these size fractions. Productivity of the soil would thus be expected to be gradually reduced as the erosion process continued. That this is the case has been reported by Uhland (1940), who shows that corn yields varied inversely with the extent of erosion. It was found by the writer (1943) that potato yields under identical conditions of fertilization and cultural practices varied from 274 bushels per acre on eroded areas to 343 bushels from relatively uneroded areas.

The extent of the reduction in productive capacity of the soil resulting from erosion is shown in a report by Lamb *et al.* (1950). Areas in corn receiving uniform fertilization of 1000 pounds per acre of 10–10–10 fertilizer show yields varying from 17 to 88 bushels per acre, depending on the amount of past erosion. Other tests showed yield variations from 40 to 106 bushels and from 54 to 82 bushels per acre, depending on past erosion. After two years of uniform cropping in an alfalfa, clover,

timothy sod, areas of Honeoye soil showed variations in corn yield from 49 to 69 bushels per acre, depending on the amount of erosion prior to the sod treatment.

The above and other reports have shown that, in general, past erosion reduces crop yields as compared with areas under similar cultural conditions where less erosion has occurred. From a comparatively long-time viewpoint, effects of grass-legume rotations in maintaining or increasing yields thus appear to be due in part to conservation effects of the rotation system.

Effects resulting from the rotation of cultivated truck crops with grass-legume mixtures at regular intervals are reported by Neal and Brill (1951). It is pointed out that the practice of growing cultivated crops in rotation with grass-legume mixtures or other close-growing, noncultivated crops has long been followed in certain agricultural areas. It is commonly recognized that such cropping practices aid in soil organic matter maintenance and in weed and disease control, and improve soil productivity. More recently it has become evident that such practices improve physical conditions of the soil, thus providing better aeration and drainage and reducing runoff and erosion losses. In many areas, however, the above factors have been only of incidental importance in determining the cropping system to be followed. Economic need has been the primary consideration. In general farming areas and on dairy and other specialized livestock farms there is commonly a need both for the cultivated grain crops and for the forage crops produced in a good rotation. In such enterprises cultivated crops are commonly grown in regular rotation with small grain and with grass-legume mixtures. The rotation study reported here, however, was carried out on a New Jersey Coastal Plain soil used for vegetable crop production. The soil type is a Freehold loamy sand. In this and similar vegetable-producing areas, little or no livestock is kept on many of the farms. The replacement of horses, as a source of farm power, by tractors and trucks has removed all need for grass and legume crops as animal feed on these farms. In this situation the decision as to whether or not cultivated crops will be grown in rotation with sod crops rests on the effects of such a rotation on soil and water conservation, on the physical condition of the soil, and on soil productivity. In the absence of immediate economic need for the forage crops, many Coastal Plain areas have been cultivated continuously during recent years in the production of vegetable crops. Despite heavier fertilization, improved methods of disease and insect control, and generally improved crop varieties and cultural practices, the acre yields of a variety of vegetable crops have declined under this system of soil management, as shown by Carncross (1948). It appears

that the influence of these several factors tending toward yield increases has been nullified by the progressively reduced capacity of the soil for production under the intensive and continuous cultivation practices followed.

In the rotation study conducted on this Coastal Plain soil, four rotations of the following characteristics were included:

Rotation I	Tomatoes, sweet corn, and peas followed by snap beans.
Rotation II	Tomatoes, sweet corn, and grass-legume sod.
Rotation III	Tomatoes, followed by 10 tons per acre compost and rye winter cover, sweet corn followed by ryegrass and vetch cover, and peas followed by ryegrass and vetch cover.
Rotation IV	Tomatoes followed by 10 tons per acre compost and rye cover, sweet corn, and grass-legume sod.

The grass-legume seeding in Rotations II and IV was made without a nurse crop in the fall following sweet corn harvest. The mixture included alfalfa; red, alsike, and crimson clover; and timothy. One cutting of hay was removed, and all additional growth left to be plowed under.

The cultivated crops in all rotations were fertilized uniformly in accordance with local recommendations. In order to balance the total fertilizer application in the different rotations, the sod mixture in Rotations II and IV received the same fertilization as the peas in Rotations I and III.

Average soil and water losses from areas in each of the rotations are shown in Table I.

Any of the rotations which included sod or regular winter cover showed soil and water losses much lower than those from Rotation I. Rotation IV, which included a year of sod, a compost application, and cover each winter, brought about the greatest reduction in soil and water losses.

The effectiveness of Rotation III in reducing soil and water losses should be interpreted with some caution as compared with ordinary farm practices for winter cover crops. In this rotation the ryegrass-vetch seeding following peas was made in July. The mixture ordinarily made a vigorous growth during the late summer and fall and occupied the land for a period of about nine months. The ryegrass-vetch seeding following corn was made in late August and occupied the land for about seven months. A compost application followed tomatoes, and a rye cover was

TABLE I

Average Soil and Water Losses under Four Rotations during a 6-Year Period

Rotation no.	Soil loss	Water loss *
	Lb./Acre	
	Average annual losses	Surface inches †
I	5130	5.53
II	2200	2.47
III	2780	2.69
IV	1600	1.81
	Average growing season ‡ losses	
I	4580	3.55
II	2090	1.71
III	2770	2.02
IV	1540	1.10
	Average winter season losses	
I	550	1.98
II	110	0.76
III	10	0.67
IV	60	0.71

* Average annual precipitation 45.81 inches.
Average growing season rainfall 28.93 inches.
† Values represent quantity of water lost as surface runoff.
‡ Includes 7-month period from April 1 through October 31.

on the land for about six months. Thus, Rotation III, although it included a cultivated crop each year, was actually out of close-growing vegetative cover for only about thirteen to fourteen months during each three-year cycle. This cropping system cannot be directly likened to one where long-season cultivated crops appear each year, with comparatively late seeding and early plowing of winter cover crops.

Evaluation of effects of the different rotations on soil properties which influence runoff and erosion can best be made by comparing losses under sweet corn and tomatoes. These crops appeared in each of the rotations. Average soil and water losses during growing seasons are shown in Table II.

The soil and water losses shown in Table II occurred during growing periods. Direct effect of sod and cover crops on runoff is not included in these averages. All areas were plowed and cultivated in the same manner during the period of measurement. It is evident that widely different amounts of soil and water loss occurred from areas under the different rotations. Losses from areas in Rotation IV, for example, were considerably less than half those from areas in Rotation I during the same periods of time. In general, Rotations II, III, and IV were more

TABLE II

Average Growing Season Losses of Soil and Water under Tomatoes and Sweet Corn in Different Rotations

Rotation no.	Tomatoes		Sweet Corn	
	Soil loss, lb./acre	Water loss, inches	Soil loss, lb./acre	Water loss, inches
I	4540	3.43	5160	4.15
II	2250	1.59	3770	2.77
III	2570	1.53	2810	2.07
IV	1800	1.05	2480	1.80

Least significant difference—Water loss 0.48 in.
Soil loss 934 lb.

or less alike in conservation effectiveness, and all were much superior to rotation I. The relative soil loss from the two crops under Rotation II is of interest. Tomatoes followed directly after the grass-legume sod crop, and sweet corn was grown during the second year of cultivation after sod. There was no winter cover between these crops. Soil loss from tomatoes in Rotation II was lower than in Rotation III, but the order was reversed during the following sweet corn crop. It appears that the compost treatment and cover crop preceding sweet corn in Rotation III had considerable effectiveness. This emphasizes a point mentioned above to the effect that frequency of application of organic matter to the soil is an important factor in structure maintenance and conservation. It appears that the conservation effectiveness of Rotation IV resulted from the fact that the substantial addition of organic matter to be expected from the sod crop was supplemented by compost and a winter cover during the following winter period.

In this evaluation of the effects of the rotations on soil and water losses, as shown in Table II, no attempt is made to separate direct effects due to improved soil physical conditions from indirect effects due to improved soil productivity. The latter is often an important factor in conservation. Improvement of soil structure, induced by the rotations, ordinarily stimulates crop growth, as will be shown later. The increased density of vegetation, in turn, provides better protection for the soil surface and thus reduces soil and water losses.

Yield data from this study show that the rotations and soil management systems most effective in reducing soil and water losses were also most effective in increasing yields of cultivated crops. This general effect would be expected. It has been shown (Johnston *et al.,* 1942; Page and Willard, 1946; Richards *et al.,* 1948) that rotations and cover crops

improve physical conditions of the soil. Other reports (Peele and Beale, 1941; Wilson and Browning, 1945) have shown the relationship of certain physical soil conditions to both runoff and erosion and to crop yields. It seems reasonable to expect that improved aggregation and porosity of the soil would permit more rapid entrance of water at the surface and more rapid percolation to lower depths of the soil profile, thus reducing runoff. These same conditions should provide better soil aeration and hence more favorable conditions for plant growth.

Average annual yields of tomatoes and sweet corn from the four rotations included in the study are shown in Table III.

TABLE III

Average Yields of Tomatoes and Sweet Corn under Four Crop Rotations, 1944–1949

Rotation no.	Tomatoes, tons/acre	Sweet corn, no. 1 ears/acre
I	12.98	9,090
II	15.34	10,010
III	13.84	11,830
IV	16.10	11,970

Least significant difference—Tomatoes 1.14
Sweet corn 682

Fertilizer applications were in accordance with local recommendations and were identical in each of these rotations throughout the period of operation. Average yields during the period of two rotational cycles varied inversely with soil losses in the different rotations. It appears, as suggested above, that soil conditions which are favorable for conservation are also favorable for improved crop growth and yield.

Similar effects of rotation with grass-legume mixtures on both yields and conservation are reported by Wilson and Browning (1945). This report shows that after cropping for fifteen years to a corn, oats, meadow rotation, corn yielded 94.4 bushels per acre in comparison with 24.4 bushels from an adjoining plot in continuous corn for the same period. The percentage of aggregates larger than 0.25 mm. for different crops was in the order: continuous corn $<$ rotation corn $<$ rotation oats $<$ rotation clover $<$ continuous alfalfa $<$ continuous bluegrass. The amounts of soil loss and runoff were in an exact reverse order.

Page and Willard (1946) show that areas in a four-year rotation of corn, oats, and two years of grass-legume sod had a degree of aggregation of 54.2 per cent and yielded 67.9 bushels of corn per acre. Areas in continuous corn showed an aggregation value of 23.4 per cent and a corn

yield of 22.5 bushels per acre. The relationship of crop rotations and soil management both to conservation of soil and water and to productivity is shown by Pierre (1945), who points out that most soil management practices aimed specifically at high crop yields also aid in the control of soil erosion and in the conservation and efficient utilization of rainfall. Wiancko *et al.* (1941) report that twenty years continuous cropping to corn reduced yields by 33 per cent despite ample fertilizer application. During the same period yields of corn following a grass-legume mixture increased from 56 bushels to 65 bushels per acre.

Browning *et al.* (1948) report that corn after eleven years of alfalfa yielded 106 bushels per acre, compared with 86 bushels on plots where a three-year rotation had been followed for twelve years, and 76 bushels an acre following eleven years of bluegrass. The yields of second- and third-year corn following eleven years of alfalfa were 83.5 and 72.9 bushels per acre, respectively. Second- and third-year yields following the bluegrass were 68.9 and 77.0 bushels per acre, respectively. Thus the corn yields following alfalfa, although higher initially, showed a more rapid decline than did those following bluegrass. Erosion losses from first-year corn following either alfalfa or bluegrass amounted to only 0.1 ton per acre. During the following two years soil loss was 15.1 tons from corn after alfalfa and 5.6 tons from corn following bluegrass.

Many reports indicate that grass is relatively more effective than legumes in bringing about aggregation and a stable structural condition in the soil. The preceding data seem to support this view.

Further data on the influence of soil management practices on physical condition and productivity of Coastal Plain areas have been reported by the writer (1952). The soil areas involved in this study are devoted largely to the production of vegetable crops. On any given farm the acreage of a particular crop may vary widely from year to year, depending on anticipated market conditions and other factors. It is thus impractical to specify a fixed rotation listing the vegetable crops to be grown. The term "land resting" was used in this situation to identify a cropping system which included two or three years of cultivation followed by a year when the land was cropped to a grass-legume mixture or other noncultivated, soil-improving crop or mixture. The land-resting practice thus limits the intensity of cultivation but does not specify the sequence or even the particular crops to be grown during periods of cultivation.

Sweet corn yields from a loamy sand soil in New Jersey following different land-resting treatments are shown in Table IV.

As pointed out earlier (Neal and Brill, 1951), each of these land-resting practices would be expected to reduce soil and water losses dur-

TABLE IV

Effect of Land-Resting Practices on Sweet Corn Production

Treatment	1947	1948	1949	Total for period
	Yield—no. 1 ears/acre			
Continuously cultivated	9,600	2,120	6,430	24,920 (4 crops)
Clover and timothy 1946	14,780	4,500	8,580	27,870 (3 crops)
Ryegrass and vetch 1946	15,810	3,650	8,380	27,840 (3 crops)
Winter cover and soybeans 1946	17,910	5,380	7,850	31,140 (3 crops)
Winter cover and broadcast corn 1946	10,180	5,800	8,140	24,120 (3 crops)

ing subsequent years of cultivation. The data in Table IV show, in addition, that sweet corn yields were increased markedly as a result of the treatments. In three of the four cases, total production from three crops following treatment exceeded that from four crops on continuously cultivated land with adequate fertilization.

The effect of these treatments on aggregation of silt and clay particles into aggregates larger than silt size is shown in Table V.

TABLE V

Percentage Aggregation of Silt and Clay Particles under Land-Resting Practices

Treatment in 1946	Aggregation (%) Fall 1946	Fall 1949 (after 3 years of corn)
Continuously cultivated	58	57
Clover and timothy	70	58
Ryegrass and vetch	65	61
Winter cover and soybeans	68	59
Winter cover and broadcast corn	68	55

Results from the samples taken in late fall of 1946 show increased aggregation of silt and clay particles under each of the land-resting treatments. Analysis of the 1949 samples shows that this effect had been largely or entirely lost in the course of three years of cultivation with annual winter cover crops. These and other data and observations have indicated that the improvements in structure and productivity of the soil resulting from land resting are temporary. The effects are largely lost during two to three years of clean cultivation. This temporary condition, however, can be permanently maintained by a systematic program of resting the land at intervals of every third or fourth year.

In addition to the above data from field plot tests, the land-resting practice was tested on a number of privately owned farms in the vegetable-producing area of the New Jersey Coastal Plain. In general, the procedure followed was to seed down an area of one-half acre or more in a field that had been under clean cultivation for several years. The remainder of the field was cultivated. Ordinarily no vegetative growth was removed from the rested area during the year. In the following year the rested area was brought into cultivation for comparison with the remainder of the field. The crop or mixture used in the resting treatment varied with the locality, with the type of cultivated crops produced on the farm, and with the grower's preference.

In a number of tests during 1950 certain physical properties of the soil known to be related to conservation were measured at the time of yield measurement. Volume weight, percentage aggregation of silt and clay particles, and amount of air-filled pore space in the plowed layer were determined for the rested and nonrested areas. Data on differences in these properties and in yield under different treatments are shown in Table VI.

Effects of the resting treatments on yields of cultivated crops and on changes in physical properties of the soils were quite variable in extent. This might be expected under the variable conditions between individual tests. The direction of change due to treatment, however, was quite consistent. In all the above cases, except one, the treatment reduced volume weight of the soil and increased air-filled porosity, degree of aggregation, and yield of subsequent cultivated crops. In the one exception the reversal of each of these trends seems to indicate failure in selection of a comparable field area for the test.

Improvement in the soil physical properties listed above has been shown to be related to reductions in runoff and erosion. A practical and effective method for maintaining favorable physical conditions in these sandy soils is through some form of land resting, as defined above. The grower following such a system will thus provide an important element in an effective conservation system and at the same time will increase acre yields, and hence efficiency of production, of cultivated crops.

V. Chemical Soil Conditioners

Recently a number of synthetic resin-like materials have been prepared, and offered on the market, for use in increasing and stabilizing aggregation of soil particles. Such materials, if proved effective, would provide the long-sought chemical means for maintenance of soil structural conditions at a favorable level. It would then be possible for the

TABLE VI

Effects of Land-Resting Treatments on Crop Yield and Change in Certain Physical Properties of the Soil

Resting treatment and year	1950 crop grown for comparison	Effect of resting treatment on yield, per cent	Change in physical properties with treatment: Vol. wt., per cent	Air space, per cent	Aggregation, per cent
Soybeans and sorghum, 1949	Tomatoes	+21	—3	+7	+10
Soybeans and Sudan grass, 1949	Peppers	+12	—2	+6	+9
Soybeans, 1949	Tomatoes	+56	—1	+2	+3
Soybeans, 1949	Tomatoes	—8	+5	—12	—8
Vetch, 1949	Lima beans	+2	—2	+2	+2
Clover-timothy, 1948, 1949	Field corn	+17	—9	+30	+7
Clover-timothy, 1948, 1949	Sweet corn	+47	—4	+15	+11
Rye and vetch	Tomatoes	+9	—6	+7	+12
Crotalaria, 1948	Field corn	+15	—3	+13	+13
Cultivated in lima beans, 1949 — Sorghum, 1948 — Cultivated in tomatoes, 1949	Sweet potatoes	+18	—4	+9	+5

land operator to purchase and apply a material for structure maintenance, thus avoiding the necessity for crop rotations which take a portion of the land out of cultivated crops at regular intervals.

Martin *et al.* (1952) report results from a study of one of the soil-conditioning materials. Application of the material at rates of 0.02–0.20 per cent of the plowed layer resulted in increased aggregation, porosity, and permeability of the treated layer. The aggregates were water-stable, and the conditioning material was highly resistant to decomposition. The improved structural condition resulting from the treatment continued through the second year of cultivation. Crop yield responses to the treatment were variable, with substantial increases occurring in some cases.

A discussion of the probable nature of the aggregating action brought about by these materials is presented by Swanson (1952). This report also cites both favorable and unfavorable cases of crop response to the treatment.

It is much too early to make an accurate evaluation of these materials as agents for maintenance of soil structure. At the moment, there seems no real possibility that compounds of this nature will replace organic matter, since organic matter in the soil has other functions in addition to improving structural conditions. It is quite possible that the soil conditioners may serve to supplement the effects of organic matter in providing a higher level and stability of aggregate formation. If further study proves this to be the case, use of these materials may make possible some change in rotation practices toward an increase in percentage of cultivated crops. Regardless of the effectiveness of these materials, the cost at the present time limits use to special conditions of high-value crops. Widespread use in general agricultural areas will require a substantial reduction below the present cost level.

VI. Summary

It is pointed out that plants require nutrients, water, and air for growth. Knowledge of the amount and availability of nutrients does not in itself provide indication of productivity. Air and water relationships are necessarily dependent on the amount and nature of pore space in the soil. Porosity, in most soils, depends on the arrangement and aggregation of soil particles. Aggregation, in turn, is influenced by several factors, of which soil organic matter is one of the more important. Of the several factors influencing soil structure, organic matter is one of the few subject to systematic management.

Reports are cited showing deterioration of soil structure as organic matter supply is depleted. Cultivation operations, in addition to the acceleration of organic matter decomposition, contribute directly to soil compaction as a result of implement traffic. Under exposure of cultivation, soil aggregation at the surface tends to break down under raindrop impact. As soil aggregates are dispersed under these influences, soil particles become most closely packed, bulk density increases, and porosity volume is decreased. These changes in the physical nature of the soil bring about reduced rates of water absorption, less favorable air-water relationships for plant growth, and increased amounts of runoff and erosion.

Systematic rotation of cultivated crops with grass-legume mixtures or other noncultivated, close-growing crops provides a practical and effective means for maintenance of favorable structural conditions in cultivated soils. Data are cited showing effects of such soil management practices on certain physical soil properties, on yields of cultivated crops, and on the extent of runoff and erosion.

A possible role of chemical soil conditioners in the maintenance of soil structural properties is pointed out.

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